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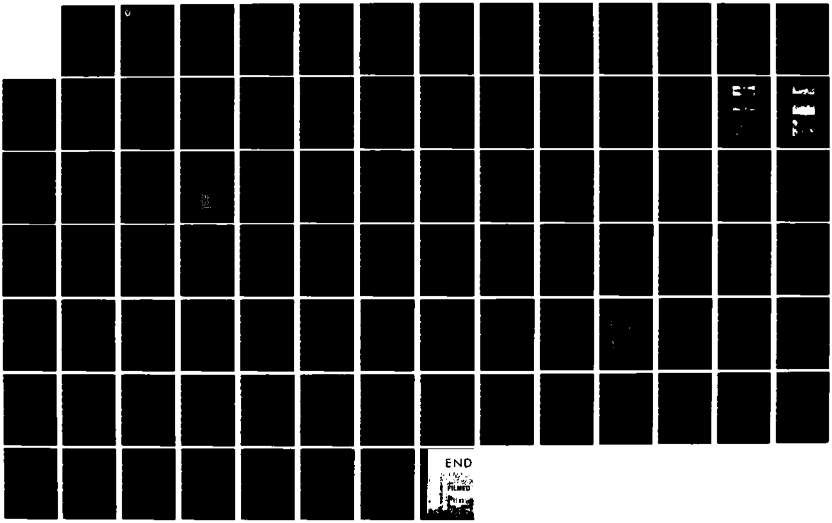

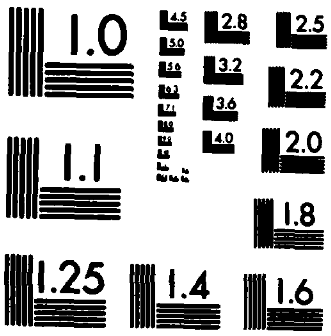

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

CECOM-83-2

AD-A134149

VEGETATION LOSS MEASUREMENTS AT 9.6, 28.8, AND 57.6 GHz THROUGH A PECAN ORCHARD IN TEXAS

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MARCH 1983

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: CECOM-83-2
2. GOVT ACCESSION NO.: AD-A134149
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): Vegetation Loss Measurements at 9.6, 28.8 and 57.6 GHz Through a Pecan Orchard in Texas
5. TYPE OF REPORT & PERIOD COVERED: Final Report, 1 Nov 1980 - 30 Sep 1982
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): E. J. Violette, R. H. Espeland and F. Schwering
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U S Department of Commerce, National Telecommunication and Information Administration, Inst. for Telecommunication Sciences, Boulder, CO 80303
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 1L1 611102.H48.PM.11.01
11. CONTROLLING OFFICE NAME AND ADDRESS: U S Army Communications-Electronics Command, Center for Communications Systems, ATTN; DRSEL-COM-RM-4. Ft Monmouth, NJ 07703
12. REPORT DATE: March 1983
13. NUMBER OF PAGES: 87
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for Public Release; Distribution Unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number): Vegetation propagation measurements; SHF-EHF; pecan orchard; loss vs tree depth
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Vegetation loss studies conducted for this report were a continuation of work reported in U S Army Report CECOM-81-CS020-F entitled, "SHF-EHF Propagation Through Vegetation on Colorado East Slope." These measurements at 9.6, 28.8, and 57.6 GHz, emphasize determining signal properties as a function of foliage depth in order to support the development of a model for predicting link performance. An evenly planted pecan orchard near Wichita Falls, Texas, was selected as the test area, which permitted controlled measurements to remove

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the density variability normally found in forested areas. In both the foliated and nonfoliated state, a sequence of measurements was made for an increasing number of trees in path, starting with one tree. For each path, azimuthal and elevation angle scans were made at terminal heights of 1, 4, and 6 meters. Additional tests, allowed determination of propagation characteristics associated with the position of the transmitter and receiver relative to a group of trees, as the transmitter was moved (position scanned) along an arc at the edge of the orchard. An abrupt change in rate of loss with tree depth in the presence of leaves, occuring between 30 and 80 meters is believed explainable by the transition from direct ray to a propagation mode where multiple scattering produced a lower loss rate.

SUMMARY

Results of a measurement program conducted in 1981 to determine the effects on millimeter wave signals propagated along paths obscured with trees, both deciduous and conifer were reported in U.S. Army Report CECOM-81-CS020-F "SHF-EHF Propagation through Vegetation on Colorado East Slope."[1] The report includes a measure of signal loss through vegetation as a function of tree depth, height above ground, foliage state (leaves and no leaves for deciduous), antenna polarization, vertical and horizontal terminal displacement, and frequency.

As a continuation of the 1981 work, this study emphasized the determination of vegetation loss as a function of foliage depth. In naturally forested areas, the density of foliage is nonuniform and difficult to describe in terms of depth. To remove the density variable, a uniformly planted orchard of pecan trees near Wichita Falls, Texas, was selected as a suitable site for measurements. This was a large, well-established and well-groomed stand of trees.

Comparative measurements were made over path lengths of 0.1 to 0.9 km (with 1 to 35 trees on path) in April 1982, when the trees were not yet in leaf and in August 1982 when the trees were in full leaf. The instrumentation used in 1981, with only slight modification, was again used for the 1982 measurements. The operating frequencies were 9.6, 28.8, and 57.6 GHz. The transmitting antennas were normally fixed at zero angle (on-path) pointing and the receiving antennas scanned $\pm$ 15° in the azimuthal plane and $\pm$ 10° in elevation. Masts on the transport vehicles provided for antenna height settings from 1 to 6 meters.

Approximately 400 individual data sets were recorded during the two measurement periods. These data were processed and compiled into tables and figures to illustrate the results of this experiment. Experimental parameters include frequency, number of trees on path, foliage depth, foliage state, height above ground, antenna pointing, and terminal position.

The following list of statements summarizes the results of this study. The figure and table numbers, reference material in this report on which the statement is based:

1. The vegetation loss measurements are first presented as a function of the number of trees on path, Figures 4.1 through 4.12, with frequency, foliage state, and terminal height as parameters. Vegetation loss in this report is defined as the signal loss due to vegetation only, independent of path length and gaseous absorption. The data show an increased vegetation loss with increasing frequency; however, the difference in loss is slight between the 28.8 and 57.6 GHz

data at the 4 and 6 meter heights with leaves on the trees. There was a clear difference in loss between the two foliage states with as much as 30 dB greater loss observed with leaves than without leaves for the 28.8 and 57.6 GHz measurements at 6 meters (Table 1).

In the absence of leaves, the vegetation loss (dB) curve as a function of the number of trees on path takes on a nearly linear shape. This shape is also present in the data at 1 meter with leaves but the leaves at 1 meter are much less dense than at the 4 and 6 meter heights. Leaves increase the vegetation loss at 1 meter but do not change the shape of the curve. At the 4 and 6 meter heights, in the presence of leaves, the loss curves have a sharp break or knee at the three-tree depth. The vegetation loss reaches levels of 40 to 60 dB through three trees and then increases much slower from that point as the number of trees increases. This abrupt change in rate of loss with tree depth in the presence of leaves is believed explainable by the transition from direct ray to a propagation mode where multiple scattering produces a lower loss rate.

2. To avoid the need to account for tree sizes and shape when dealing with propagation losses through trees, a preferred method to describe vegetation loss is in terms of foliage depth. The foliage depth per tree for the pecan orchard was estimated to average 9 meters at the 4 meter height and 11 meters at the 6 meter height. With these depth estimates, the measured loss for the 4 and 6 meter heights are plotted in Figures 4.16, 4.17, and 4.18, respectively, for 9.6, 28.8, and 57.6 GHz. These curves have loss values and shapes that correspond to the data in Figures 4.8 and 4.12. Superimposed in Figures 4.16, 4.17, and 4.18 are curves predicting vegetation losses using a modified exponential decay model.[2] This model predicts a linear decay to 14 meters and an exponential decay from 14 to 400 meters.

3. Azimuth and elevation angle scans of antenna pointing with 1, 3, 8, and 11 trees in the path for no leaf and in-leaf conditions are presented in Figures 4.19 through 4.24. These show essentially no directivity remaining in the received signal after 8 trees without leaves and after 3 trees with leaves. Within the 30 degree azimuthal and 20 degree elevation scan angles, the results indicate that the foliage illuminated by the transmitter, through a combination of direct radiation, and diffractive and reflective propagation modes, provides a nearly uniform signal intensity after the number of scatterers reach a point which in this experiment is equivalent to approximately 8 trees without leaves and 3 trees with leaves. There was no over the top or canopy mode detected in the elevation scans. No increase in

signal was observed at the outer edge of the trees in the azimuth scan, suggesting that a down the row mode was not prevalent.

4. The majority of records for this experiment were made with the transmitter and receiver aligned such that a portion of a tree row was positioned carefully in the propagation path. This method produced a consistent measure of foliage depth to compare vegetation loss as a function of depth. Several additional tests were conducted with the transmitter and receiver initially positioned such that a line-of-sight path lies between rows and then the transmitter was moved (position scanned) along an arc at the edge of the orchard. These tests allow determination of propagation characteristics associated with position of the transmitter and receiver relative to a group of trees. The received signal amplitude data in Figures 4.25 through 4.29 show this position in the orchard.

Three paths were examined using a position scan where one terminal was continuously moved over a distance that is large relative to tree size. The first was for a non-line-of-sight path (without leaves) through 500 to 700 meters of dense (closely spaced) trees which resulted in an average signal loss of only 25 dB below free space where propagation is primarily by diffraction from tree trunks. The second centered around a line-of-sight path (without leaves) of up to 700 meters where much less than first Fresnel zone clearance existed on the path which produced less than a 10 dB loss over free space. The third position scan centered around a line-of-sight path (with leaves) where more than a first Fresnel zone clearance existed on the path which resulted in essentially free space signal levels. There was also a periodicity noted in the signal amplitude for these scans resembling a grating effect probably produced by the grid-like pattern of trees within the orchard.

5. Results from the tests conducted in 1981 and the tests in 1982 indicate that the received signals are highly dependent on relative position and pointing angle of the antennas in the orchard, when measurements are made with a row of trees on path. The position of the terminal not in the trees has less effect on the received signal for small displacements compared to the size of the trees. Data in Figures 4.30, 4.31, and 4.32 show received signal amplitude as a function of horizontal position ($\pm$ 70 cm) of the terminal in the orchard relative to the initial on-path alignment. These data show signal amplitude changes of more than 20 dB for horizontal changes of not more than 10 cm. The presence or absence of leaves had little effect on these amplitude variations (Figures 4.33, 4.34, and 4.35).

6. Plots of horizontal scans with small displacements relative to tree size were compared with the antennas linearly and cross polarized as shown in Figures 4.38 through 4.40 for 8 trees with leaves in the path. At the trunk height of 1 meter in Figure 4.38, little depolarization was apparent and signal variations were mainly a function of terminal position. At terminal heights of 4 and 6 meters, up to 19 dB of depolarization occurred with the 28.8 GHz producing somewhat more than the 9.6 or the 57.6 GHz in this situation.

7. As in the previous Colorado measurements no change in loss was observed as a function of antenna polarization, either horizontal or vertical.

8. No change in loss was observed for times of high relative humidity (near 100%) compared to times of relatively low humidity (30%). Rain did not occur during either measurement interval.

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I. INTRODUCTION

A measurement program was conducted in 1982 to determine the effects on millimeter wave signals propagated along paths obscured with deciduous and conifer trees. The objective of the project was to obtain information on signal loss as well as spatial, polarization, and scattering characteristics for propagation through a variety of foliage and atmospheric conditions at 9.6, 28.8, and 57.6 GHz. Results of this work are reported in U.S. Army Report CECOM-81-CS020-F entitled "SHF-EHF Propagation through Vegetation on Colorado East Slope."[1] The principal results of the 1982 work included a measure of signal loss through vegetation as a function of tree depth, height above ground, foliage (leaves and no leaves for deciduous), antenna polarization, vertical and horizontal terminal displacement, and frequency.

In 1982 the vegetation studies for the U.S. Army continued with emphasis on determining signal properties as a function of foliage depth in order to support the development of a model for predicting link performance. In forested areas, the density of foliage was found to be nonuniform and difficult to describe in terms of depth. An evenly planted orchard permits a controlled measurement removing the density variable. Because of the tree size, foliage density, and humid climate, a pecan orchard near Wichita Falls, Texas, was selected as best suited to the measurement requirements.

This report contains the results and analysis from measurements made at the pecan orchard in April 1982, before the trees were in foliage and in August 1982 when the trees were completely in leaf. The data include measurements over path lengths from approximately 0.1 to 0.9 km with 1 to 35 trees on path. Most of the measurements were made with the terminals carefully positioned such that a row of trees was directly in the transmitter-receiver path. A sequence of measurements was made for an increasing number of trees in path, starting with one tree. The transmitter and receiver locations were carefully noted, to allow a replication of measurements in the foliated state. For each path, azimuthal and elevation scans were made at terminal heights of 1, 4, and 6 meters. Other measurement variables included antenna polarization and the transmitter antenna horizontal and vertical position.

A series of special measurements were made with the terminals at 1 meter height. This series was conducted with the receiving terminal located between rows and the transmitter terminal moving along an arc at the edge of the orchard. This test provided a measure of signal levels for conditions where the receiver

was looking directly between a row of trees and the transmitter was positioned for: a non line-of-sight path, a path with less than first Fresnel zone clearance, and a path with greater than first Fresnel zone clearance.

An initial system gain calibration was made on a far-field path chosen to be free of obstructions and ground reflections, and additional calibrations were performed periodically during the measurement program to verify system gain stability.

II. EQUIPMENT AND CALIBRATION

The millimeter wave instrumentation that was developed to measure signal characteristics between terminals positioned on paths obstructed by vegetation and used in 1981 to measure propagation through vegetation on the Colorado East slope[1] was modified slightly to improve terminal mobility and to increase link sensitivity, primarily in the 57.6 GHz channel. The elevator towers at both terminals were reduced from 9 meters to 6 meters thus eliminating requirements for tower guying, and for the second half of this test series an additional active source was added to the 57.6 GHz transmitter to increase the output level. The receiving antennas and the rf hardware are mounted on a remote-controlled positioner, permitting both azimuthal and elevation scans at all elevator heights. The transmitting antennas and rf hardware are mounted directly to the terminal elevator. All antennas can be readily set for vertical or horizontal polarization, allowing linear or cross-polarized measurements.

The link operates at three coherent frequencies: 9.6, 28.8, and 57.6 GHz. Beamwidths of the transmitting antennas are 10 degrees at all frequencies. Receiver beamwidths are 4.8 degrees at the 9.6 GHz frequency and 1.2 degrees at 28.8 and 57.6 GHz. A 60 dB dynamic range limited by the last IF amplifier stage and a minimum sensitivity of -100 dBm is available at all frequencies.

A. Instrumentation Description

A functional diagram of the transmitting terminal is shown in Figure 2.1. All three rf frequencies are derived from a 100 MHz temperature compensated crystal oscillator. A phased-locked, cavity-tuned (X96) multiplier is used to generate 30 mW at 9.6 GHz. An identical (X96) multiplier drives a varactor tripler which injection locks an 85 mW Gunn source at 28.8 GHz through a high isolation ferrite circulator. The Gunn power is fed to a directional coupler providing 20 mW to a 25 dB gain horn antenna, and the remaining power drives a varactor doubler. A directional coupler is used to inject a locking signal from the doubler into the 57.6 GHz IMPATT source. With a bias current of 260 ma, the IMPATT provides 120 mW to a 25 dB gain horn antenna. The entire transmitter is mounted in a temperature controlled enclosure which is held at 45°C $\pm$ 1°C to reduce power variation to less than $\pm$ 0.5 dB at 57.6 GHz in the worst case. The transmitter enclosure is attached to the vertical carriage of the van.

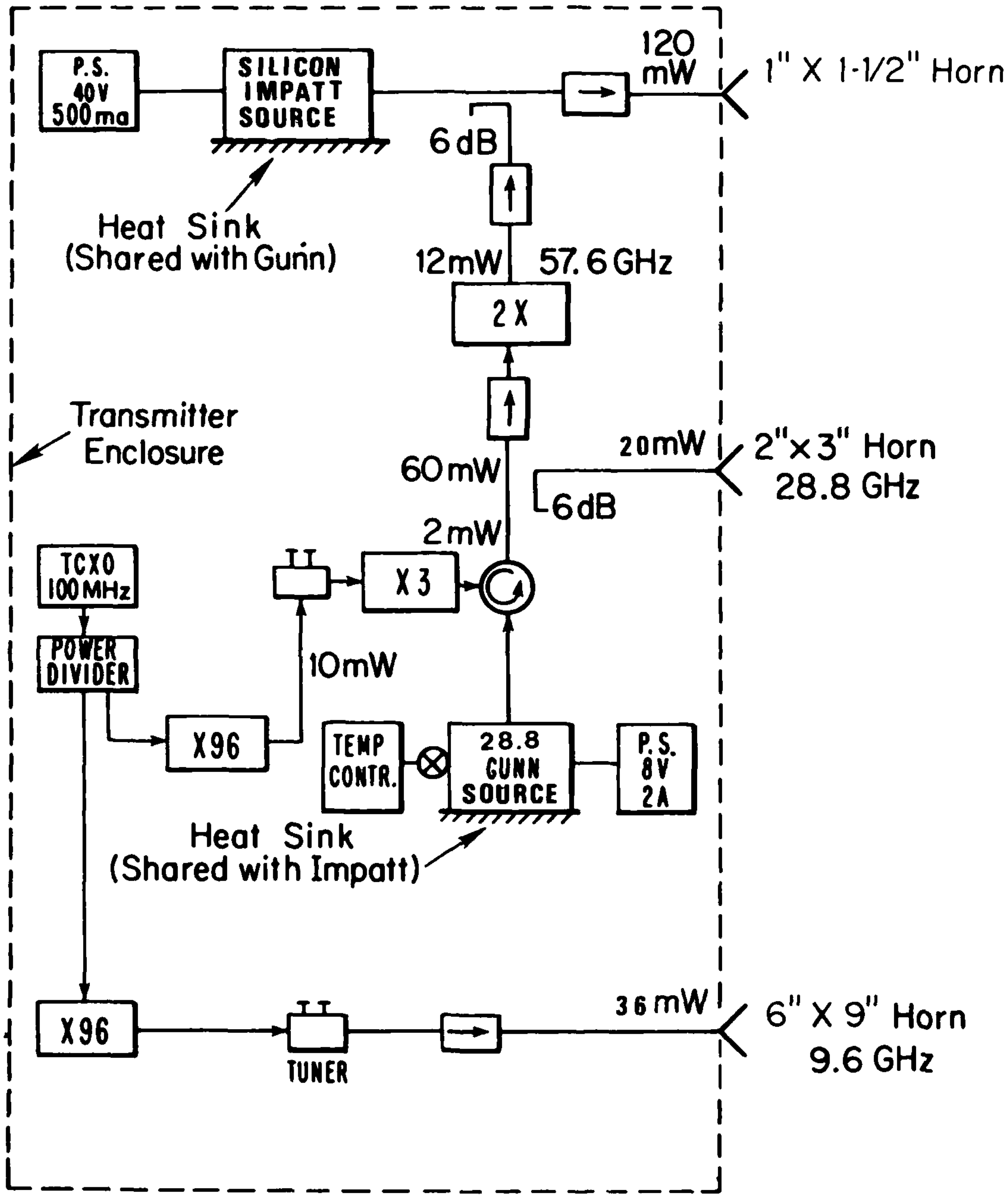

Fig. 2.1. A functional diagram of the transmitting terminal.

A functional diagram of the receiving terminal is given in Figure 2.2. All of the receiving rf components and the low noise IF preamplifiers are contained in a 45° $\pm$ 1°C temperature controlled enclosure. Three parabolic reflectors (18, 24, and 12-inch), in the order of ascending frequency, are mounted on the enclosure with low-noise down converters coupled directly to the antenna feeds. This total assembly is mounted on the remote controlled positioner. The receiver noise figure is determined by the input down converter, which is a double-balanced mixer at 9.6 GHz with a 7.5 dB double sideband noise figure. The 28.8 and 57.6 GHz input mixers are of the stripline-waveguide-junction balanced type with double sideband noise figures of 5.5 and 6.0 dB, respectively. All local oscillator (LO) signals are generated from a voltage controlled crystal oscillator which is phase locked to the 9.6 GHz received signal with an 80 kHz reference offset frequency. The multipliers for the voltage controlled 100 MHz reference ($\pm$ IF/multiplying factor) to derive the LO injection signals are identical to the scheme used for the transmitter sources, except, at 57.6 GHz, the doubler alone provides sufficient LO level. Long term (weeks) gain stability for each receiver is better than $\pm$ 0.1 dB.

A block diagram of the data acquisition system is shown in Figure 2.3. The three IF frequencies of 80, 240, and 480 kHz are brought to the receiving van via coaxial cables, filtered, and amplified before entering an ac to dc log converter. The received IF signals are converted to a dc level that is logarithmically related to the rf signal amplitude. These dc levels drive a multi-channel strip chart recorder for monitoring, and they also appear at the input of a digital scanner which is capable of switching between each receiver level at rates of up to 30 times per second determined by the data-logging desk computer. The desk computer is also interfaced with a 5-1/2 digit voltmeter and is programmed to perform data collecting, data processing, tape storage, and data plotting functions.

B. Calibration and Path Characterization

The initial instrumentation calibration was performed on a far-field path of 300 meters. A definition of a minimum far-field distance is $d_{min} = 2D^2/\lambda$, where D is the receiving antenna aperture, and λ is the rf wavelength. The calibration path was chosen to be free of any significant reflecting components from either ground or above ground obstacles so that the on-path signal amplitude is not altered. For path lengths of less than 2 km and consistent with the system measurement accuracies, only the molecular oxygen absorption losses at 57.6 GHz need to be included. At Wichita Falls, TX, where the elevation is 150 meters above sea

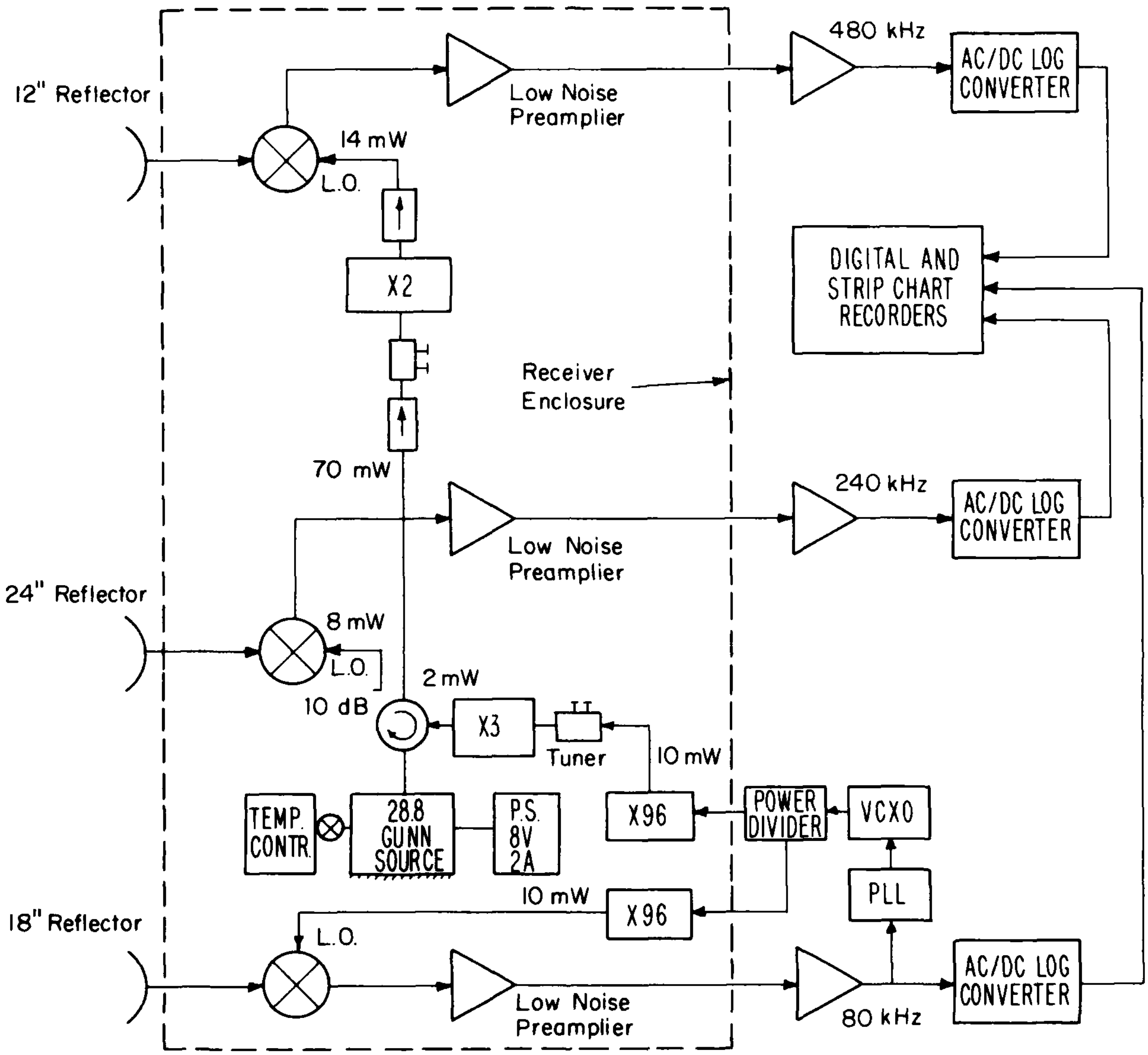

Fig. 2.2. A functional diagram of the receiving terminal.

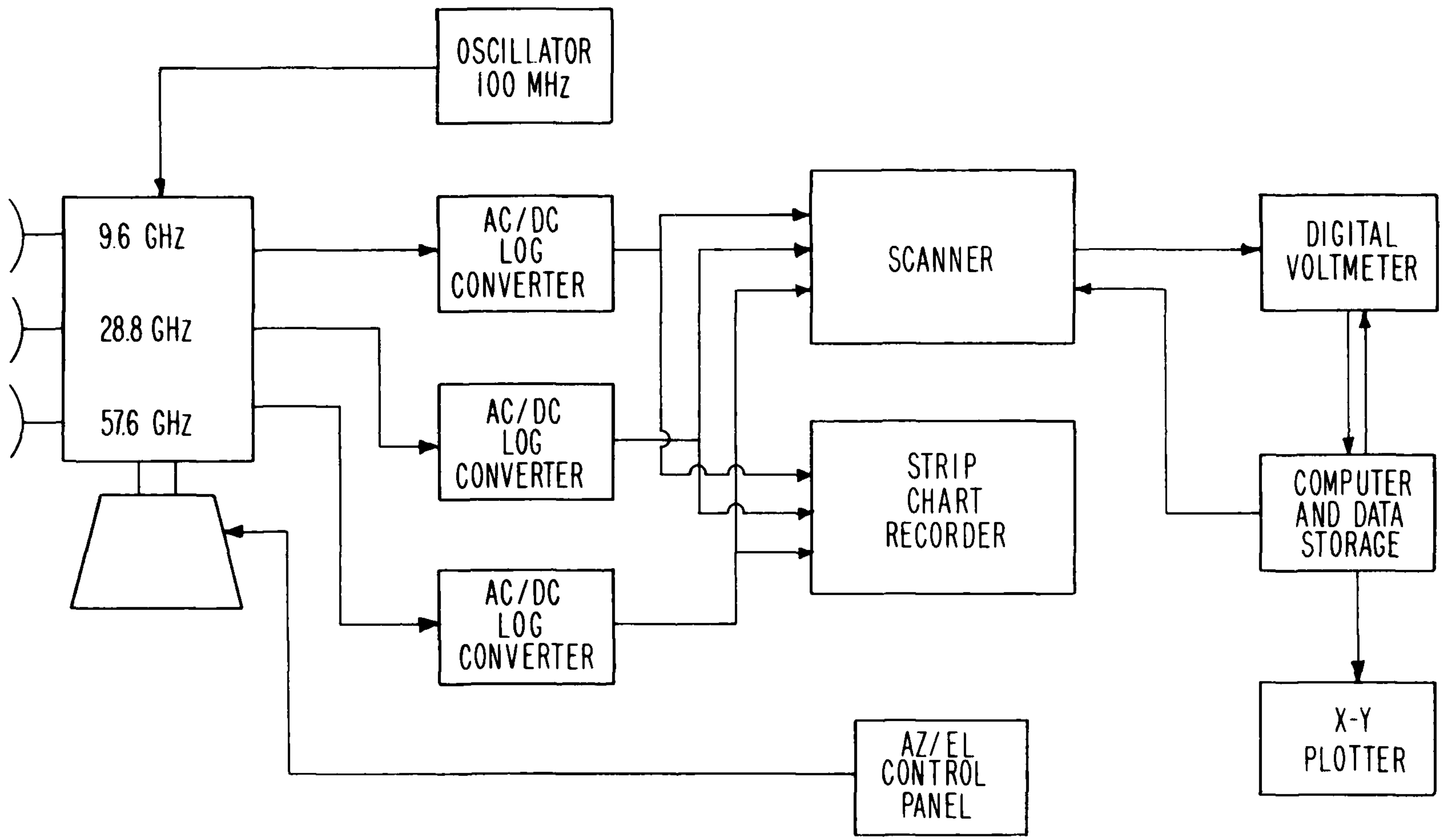

Fig. 2.3. A block diagram of the data acquisition system.

level, the attenuation at 57.6 GHz is 12.0 dB/km; that value is used for all path calculations. By comparison, losses at 9.6 GHz are 0.006 dB/km and at 28.8 GHz are 0.017 dB/km, with an ambient temperature of 20°C and 50% relative humidity. The signal amplitude values presented in the later sections are relative to free space with molecular oxygen absorption loss corrections applied to the 57.6 GHz data only.

C. Field Data

The field data are recorded on a strip-chart and digital tape. The received signal amplitude values are obtained from a play-back of the digital tape normalized for path length and attenuator settings. The strip-chart data provide a data back-up and log-book verification.

The primary data formats were a recording of the received signal amplitude as a function of azimuthal and elevation angle scans of the receiving antennas, the horizontal positioning of the transmitting antenna, and a vertical position scan of the receiving antenna. The link configurations used to obtain these data are represented as pictorial diagrams in Figure 2.4. Representative signal traces are also shown in this figure. A description of each configuration and a comment on the data obtained follows:

1. Azimuthal Scans

In this configuration, the transmitter and receiver are set at a fixed separation distance and the receiver is scanned in azimuth. Far-field calibration runs were performed in this mode.

2. Elevation Angle Scans

The transmitter and receiver are set at a fixed separation distance and the receiver is scanned in elevation angle. Calibration runs are also made in this configuration.

3. Horizontal Positioning

The transmitter and receiver are set at a fixed separation distance and the transmitter is moved horizontally relative to the on-path center. The horizontal off-set is small compared to the transmitter-to-receiver path length, consequently the received signal variations are due mainly to obstructions (vegetation) on-path.

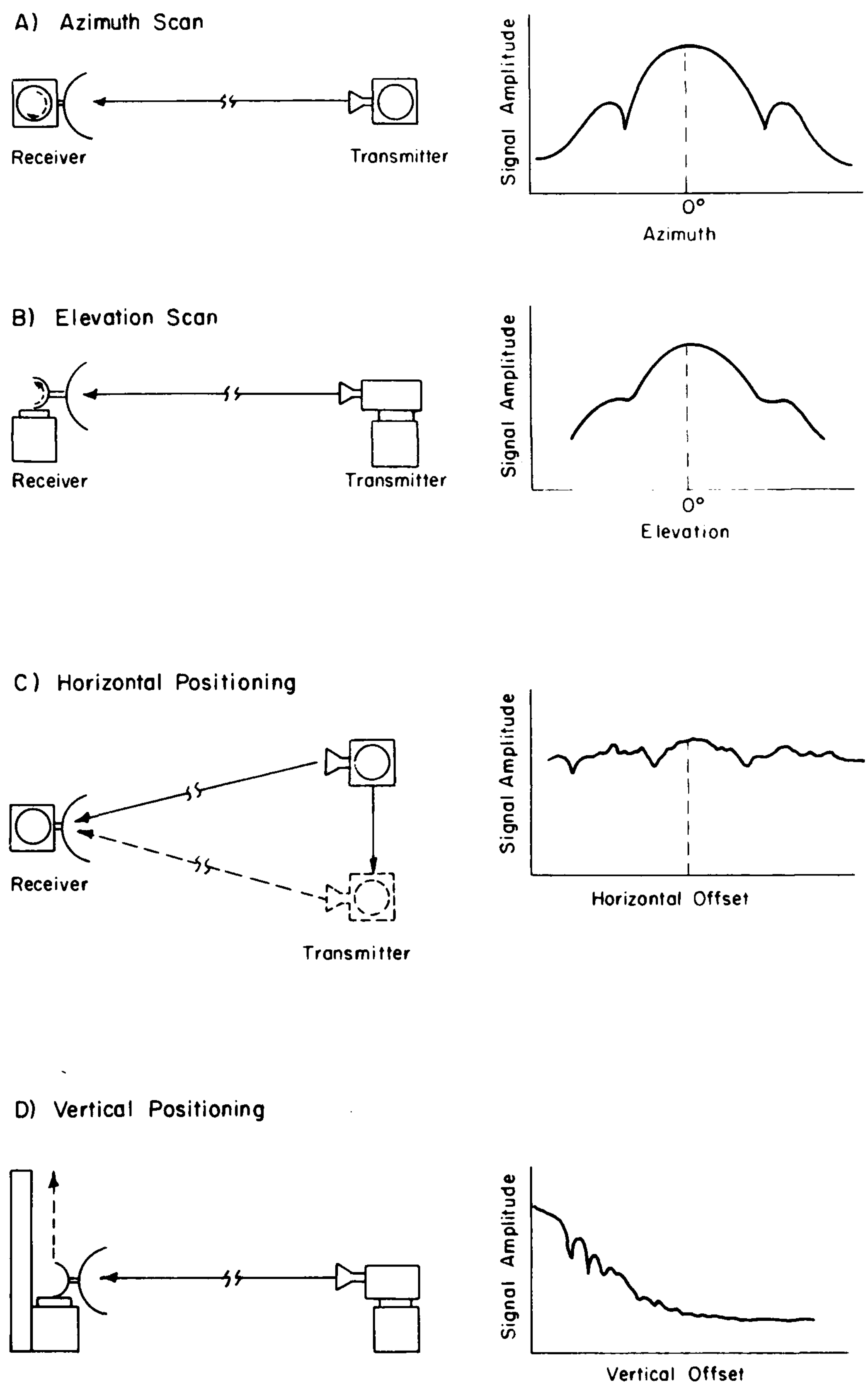

Fig. 2.4. Test link operating configurations.

4. Vertical Positioning

The transmitter and receiver are set at a fixed separation distance and the receiver is moved vertically relative to a selected height. The vertical travel is small compared to the transmitter-to-receiver path length; consequently, the receiver signal variations are due mainly to obstructions (vegetation) on path.

III. MEASUREMENTS

The segment of the Chitwood Pecan Orchard near Wichita Falls, Texas, used for these tests was a well-established and well-groomed stand of trees. These trees were planted in a square grid with a tree spacing of approximately 13 meters and have now attained heights of 8 to 10 meters. The maximum span of branches reached 10 to 13 meters, filling the space between rows in many areas. The initial branching occurs at the 1.5 to 2.0 meter height showing significant branching at the 4 and 6 meter levels, leaving mainly trunks at the 1 meter level. When the trees are in leaf, the weight of the new growth of twigs, and nuts cause the branches to droop, such that some foliage extends down to the 1 meter level. The leaves of the pecan trees grow in clusters of 10 to 12 leaves on each twig. The leaves are arranged on the twig in balanced symmetry and range in size from 5 cm long and 2 cm wide near the branch to 20 cm long and 5 cm wide at the end of the twig. In April, during the time of the defoliated measurements, a grain crop planted as a temporary ground-cover had attained a height of 10 to 15 centimeters, providing a uniform clean-looking ground plane free of weeds and underbrush. The pictures in Figure 3.1 were taken of the grove in early April. The first picture (a) shows the uniform planting of the trees. In picture (b), the receiver is located with one tree on path. In picture (c), the scene includes the receiver van looking toward the transmitter with several trees on path. The unit on the tripod provides the 9.6 GHz phase-locked signal. An arrow points to the transmitter site.

In August, the trees were in full leaf and the nuts had grown to nearly full size. The ground-cover had been turned under leaving essentially no foliage on the ground. However, at the base of some trees, areas with diameters of 2 to 3 meters were missed, leaving a .5 meter stand of weeds. The pictures in Figure 3.2 were taken in the middle of August. Picture (a) shows the full leaf condition of the orchard and picture (b) shows the van behind one tree, nearly hidden by leaves. The view in picture (c) is taken from the side showing the van and mast. The receiver is at a 6-meter height. The undergrowth around some of the trees can be seen in this picture.

The drawing in Figure 3.3 shows the locations of the transmitter and receiver in relation to the orchard and an open field adjacent to the orchard. The measurement paths listed in Table 3.1 are identified by a transmitter and receiver designation. The first path listed in Table 3.1 is T_3/R_2 indicating that the transmitter was at location T_3 and the receiver was located at R_2 (these locations are identified on Figure 3.3). Most of the measurements were taken on a line through the center of

a

b

c

Fig. 3.1. Photographs of the test orchard taken in April 1982. The trees were free of leaves.

a

b

c

Fig. 3.2. Photographs of the test orchard taken in August 1982. The trees are in full leaf.

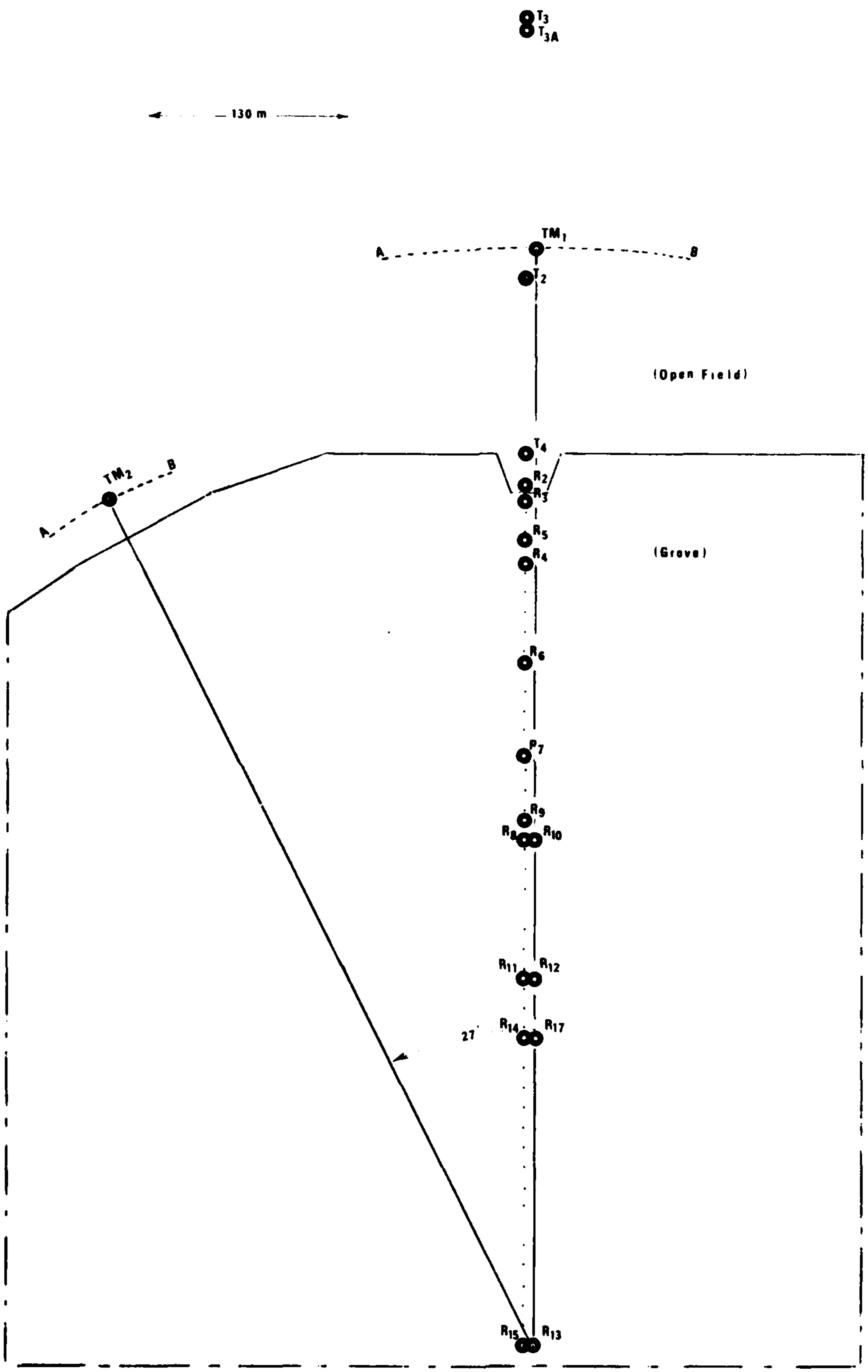

Fig. 3.3. A drawing of a portion of the pecan orchard showing the transmitter and receiver test locations.

TABLE 3.1

Measurement Paths

PATH	CODE TRANSMITTER	RECEIVER	PATH LENGTH (m)	NO. OF TREES
Calibration	T_3	R_2	308	None
"	T_{3A}	R_2	300	"
"	T_3	R_{10}	530	"
		No Foliage		
Fixed length	T_2	R_3	107.5	1
" "	T_2	R_4	140	3
" "	T_2	R_5	121.5	3
" "	T_3	R_5	338.5	3
" "	T_3	R_4	357	3
" "	T_3	R_6	435	8
" "	T_3	R_7	483	11
" "	T_3	R_8	530	14
" "	T_3	R_9	523	14
" "	T_3	R_{11}	620	20
Mobile	TM_1	R_{13}	720	Variable
"	TM_2	R_{13}	620	"
		With Foliage		
Fixed Length	T_{3A}	R_3	315	1
" "	T_{3A}	R_4	350	3
" "	T_{3A}	R_5	343	3
" "	T_{3A}	R_6	420	8
" "	T_4	R_6	138	8
" "	T_{3A}	R_7	468	11
" "	T_{3A}	R_8	520	14
" "	T_{3A}	R_{11}	612	20
" "	T_{3A}	R_{14}	662	23
" "	T_{3A}	R_{15}	869	35
" "	T_{3A}	R_{16}	860	35
Mobile	TM_1	R_{17}	507	Variable

a row of trees. Nearly all the receiver locations lie on this line. Receiver locations not on this line, R_{10}, R_{12}, R_{13}, R_{17}, are in the space between the "test" row and an adjacent row. The transmitter locations are on an extension of the line through the "test" row of trees, except for the two transmitter mobile paths. For some of the data taken in August (in foliage), several paths were established with the transmitter at a designated receiver site and the receiver at a designated transmitter site, thus placing the transmitter in the orchard and the receiver in the open field. The outlined area in Figure 3.3 encloses the test area of the orchard. The solid line nearest the transmitter locations, approximates the edge of the orchard. The broken lines at the side and bottom of the drawing identify the remainder of the test area. The enclosed area was uniformly planted except for an occasional open space where a dead tree had not been replaced. The orchard extended many hundreds of meters on the sides and back of the test area.

A segment of Figure 3.3 showing the primary transmitter locations and the first five receiver locations is redrawn to larger scale in Figure 3.4. In this drawing, the larger dark circles represent trees and show the exact placement of the first eight trees in the "test" row. These circles do not represent the actual size of the trees and in many cases, branches of adjacent trees overlapped. The open spaces represent areas where a tree is missing. Most of the receiver sites were selected at a space where a tree was missing, which made positioning of the receiver van much easier than trying to locate between two adjacent trees in the row.

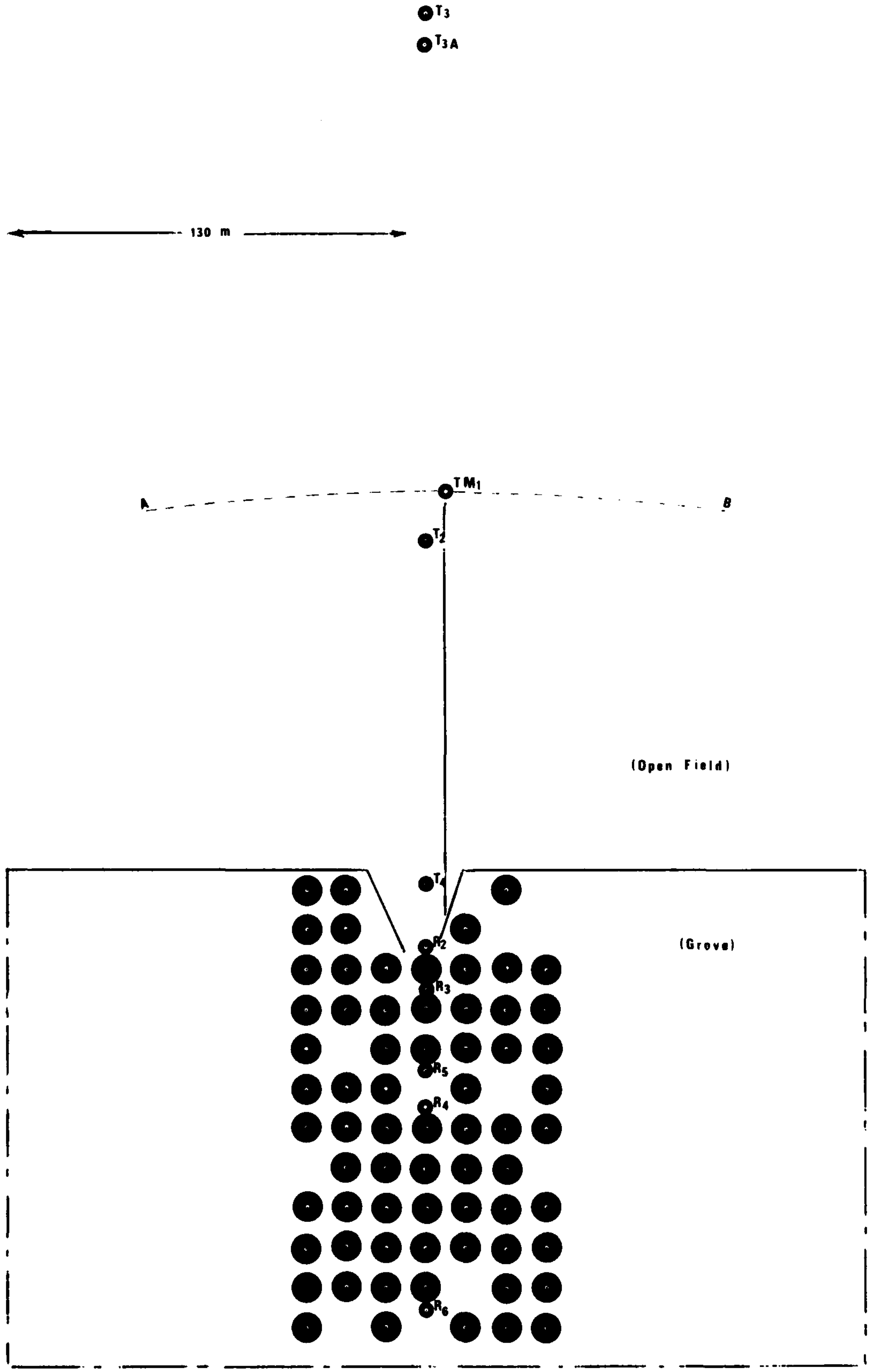

Fig. 3.4. A drawing of a portion of the pecan orchard showing some transmitter and receiver test locations with tree locations.

IV. ANALYSIS OF SIGNAL CHARACTERISTICS THROUGH TREES

Principally, two types of measurements were made in these tests. The first was with the transmitter and receiver located to measure the vegetation loss through trees at the 1, 4, and 6 meter levels, for a varying number of trees in the path. Combinations of transmitter locations T_2, T_3, T_{3A}, and T_4, and receiver locations R_3, R_4, R_5, R_6, R_7, R_8, R_9, R_{11}, R_{14}, R_{15}, and R_{16} established these paths. For each path, the transmitter and receiver were carefully positioned to provide the desired geometry. A description of these paths is given in Table 3.1, listed separately for no foliage and with foliage. They are defined by tree depth and the listing in the table gives the respective transmitter and receiver locations and the total path length. The total path length is the distance in meters between the transmitter and the receiver and is never totally covered by trees in these measurements. The depth of foliage on a path is the product of the number of trees on the path and the nominal depth of foliage per tree at a given height. The depth of foliage at the 4 and 6 meter heights is in the range of 10 to 13 meters.

The second type of measurement made at this site was to provide an indication of the spatial characteristics by continuously moving one terminal with the second fixed behind a substantial number of trees. Transmitter locations TM_1 and TM_2 and receiver locations R_{13} and R_{17} were used for three observations in which the transmitter was moved along an arc so that it's tangent was perpendicular to the transmitter-receiver line. The orchard structure and number of trees in the path continually varied with transmitter location. In the defoliated state, the path was line-of-sight for a small segment of the arc, however for the same test configuration with leaves, the path was never line-of-sight.

The test and figures in this section describe the observation of signals propagated through various paths with trees, in order to identify and assign values to vegetation loss and propagation parameters where possible. Measured as a function of depth of foliage or number of trees (without foliage), these parameters include antenna pointing, antenna polarization, spatial, temporal, and frequency dependence of vegetation loss.

Discussions pertaining to the recorded data, graphs plotted from the data, and photographs of the trees and paths are separated into the following categories:

a) <u>Loss vs. tree depth</u>

These data are sets of curves showing amplitude dependence on the number of trees in the path. The data includes measurements at three frequencies and three antenna heights. These curves include results from measurements made with and without leaves.

b) Loss vs. foliage depth

In this section the data were reduced to show vegetation loss as a function of foliage depth.

c) Horizontal scans of the orchard

Scans were made with the transmitter moving in an arc at the perimeter of the orchard. This measurement provides a uniform path length, with continually varying tree density and placement at trunk level height.

d) Horizontal displacement scans

These measurements show signal variation as a function of horizontal position perpendicular to the path with small displacements relative to tree size. Maximum scan displacements were ± 0.7 meters.

e) Signal depolarization

Depolarization effects are presented for 8 trees in foliage.

f) Vertical vs. horizontal polarization

Comparisons are made of vegetation losses as a function of antenna polarization.

g) Reversal of transmitter and receiver positions

The greater portion of vegetation loss measurements were made with the receiver in the orchard and the transmitter in an open field. Some sample tests were made with these positions reversed.

h) Receiver position relative to the first tree on path

Measurements were made with the distance of the receiver terminal to the first tree varied.

A. Loss vs. Tree Depth

The emphasis of this study was placed on determining signal properties as a function of the number of trees on path. Data sets were recorded with 1, 3, 8, 11, 14, 20, 23, and 35 trees obstructing the path. The data used in this section to determine vegetation loss as a function of tree depth is taken from the combined azimuthal and elevation scans where the terminals were carefully positioned at trunk level on a line that passed through the center of the tree row. Each recorded value is adjusted to compare to the free space level that would have occurred without path

obstructions. In other words the signal reduction due to path length and atmospheric absorption was removed so that only the loss due to the path obstruction (trees) is indicated. Values recorded for this purpose are the highest measured received signal level that occurred on either the azimuthal or elevation scan. There was concern that the maximum signal may not have occurred within the horizontal-vertical slice taken across the 0° intercept. Tests were conducted incrementing one axis by ± 1 or 2 degrees and repeating the scan for the other axis. This process was repeated for several tree depths particularly if a null occurred for the zero pointing scans. At no time was a higher level observed than that found on scans that passed through the 0° intercepts.

Data shown in Figures 4.1 through 4.12 are a composite of all the measured values for a particular tree depth. The data points plotted for each tree depth includes a vertical to vertical (VV) and horizontal to horizontal (HH) antenna polarization. The signal level may differ by several dB, seldom more than 10 dB, but this difference was determined to be due to the fact that the antenna center position changed by a few centimeters when the antennas were mechanically repositioned for the polarization change. There was no consistent change in signal level due to polarization detected so any polarization dependence is presumed small compared to other variables such as spatial dependence.

In addition to data points for each polarization, the plots in Figures 4.1 through 4.12 may include a measurement at an early morning hour at which time the relative humidity of the atmosphere was highest and a second measurement near midday when the relative humidity is usually at a low point. Humidity for these tests ranged from near 100% (no rain occurred during the experiment) down to approximately 30%. Data points from these measurements never varied by more than ± 1 dB so they were always represented by a single point.

Other data points used for the vegetation loss plots were for a condition when the terminal in the trees was returned to a particular location after collecting data for other tree depths. Each terminal position could be relocated to within a few centimeters of it's original location and loss values would repeat within less than 1.0 dB. An exception to this repeatibility was during windy conditions. Some data points are for the case where the transmitter was located within the orchard and the receiver was outside. A few data points are for cases where the receiving terminal was located at distances of greater than 15 meters or less than 7 meters from the trunk. For some tree depths, as many as seven measurement points are available for each test frequency. At each tree depth, data as described above were recorded for terminal heights of 1, 4, and 6 meters.

Figures 4.1, 4.2, and 4.3 show the spread and the average value of the measured vegetation loss at the 1 meter height for 9.6, 28.8, and 57.6 GHz, respectively, for the foliated and defoliated tree states. Figures 4.5, 4.6, and 4.7 display the same data for the 4 meter height and Figures 4.9, 4.10, and 4.11 for the 6 meter height. The average vegetation loss at the 1 meter height for each frequency is plotted relative to number of trees in the path in Figure 4.4. Figure 4.8 contains the average vegetation loss at the 4 meter height and Figure 4.12 for the 6 meter height.

The average value plots of Figures 4.4, 4.8, and 4.12 permit an analysis of the vegetation loss dependence on the number of trees, on frequency, and on height of the terminals. At the 1 meter height, Figure 4.4, the loss was more or less a linear function of the number of trees except for some of the points taken for 1 tree on the path. At 28.8 and 57.6 GHz a higher loss occurred for 1 tree than for 3 trees which was not the case for the 9.6 GHz. The loss for 1 tree is sensitive to the position of the antenna relative to the center of the trunk since the antennas could not be absolutely colocated. The centers for the two higher frequency antennas lie in nearly the same vertical plane, seeing the obstruction somewhat differently than the 9.6 GHz receiving antenna. Also, the 9.6 antenna beamwidth is 5 degrees, about 4 times that of the upper two frequencies, and is large compared to the angle subtended by the trunks as seen by the receiver. The losses at each tree depth are consistently higher with increased frequency. The presence of leaves in the vicinity of the 1 meter height and some tall grass would be expected to produce a greater loss for the upper two frequencies.

The propagation mode for these signals must be primarily diffraction scattering from the trunks since little signal would pass through the 40 to 50 centimeter diameter trunks. Because of variations in trunk size and positions relative to the antenna beam, the geometry is quite complex. Antenna scans plotted in the next section show that the maximum signal arrives from the direction of one or the other edge of the trunk nearest the receiver.

In the data at the 4 meters height, Figure 4.8, an abrupt break in the plot of vegetation loss versus number of trees can be seen. In the case of no leaves, the break occurs after the 8-tree point. For the measurements with the trees in leaf, the break in the curve is very pronounced after 3 trees. It is assumed that this break occurs when the dominant propagation mode changes from the strongly attenuated direct path mode (coherent component) to the multiple-scatter mode (incoherent component).

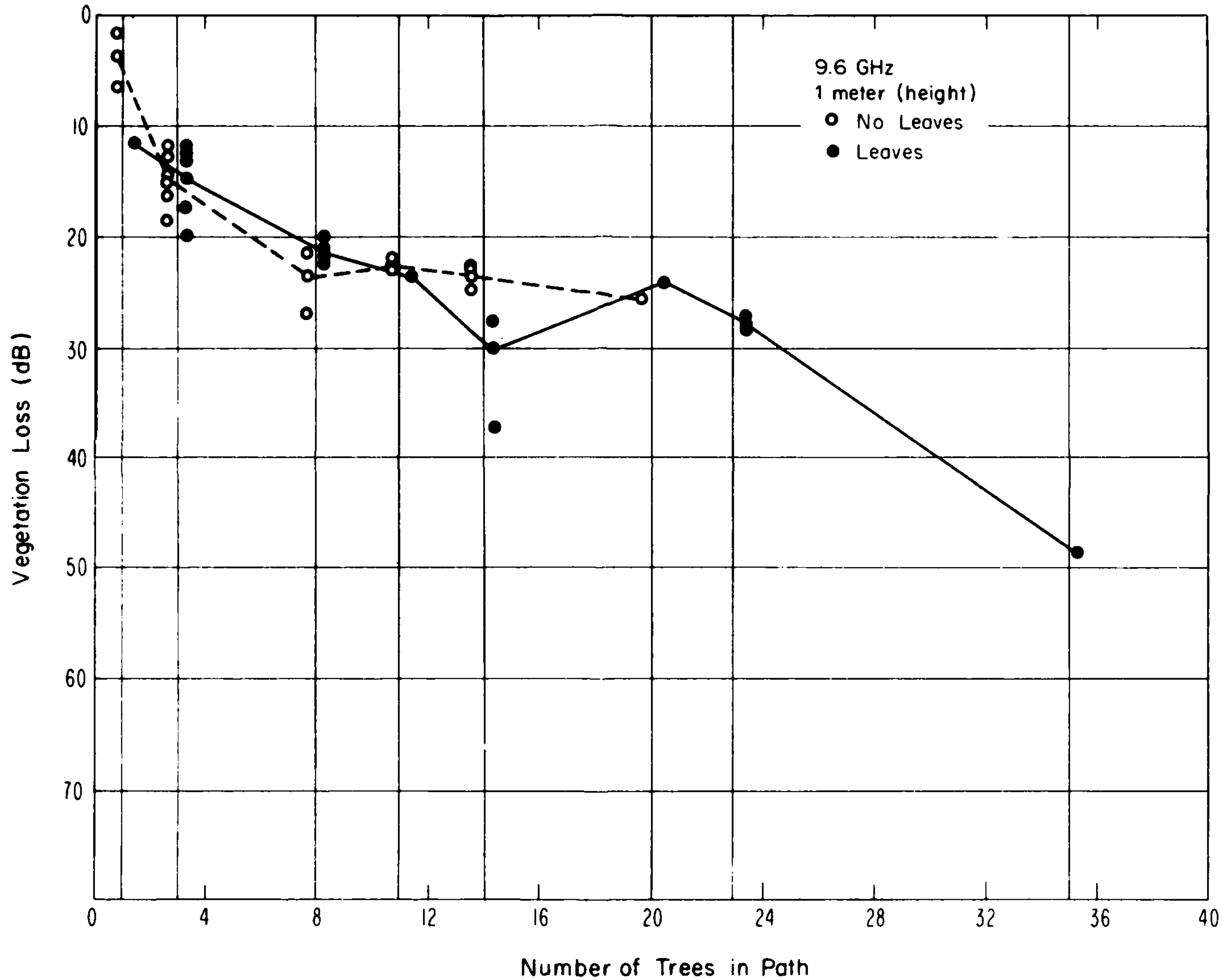

Fig. 4.1. Vegetation loss as a function of the number of trees in path for 9.6 GHz at 1 meter.

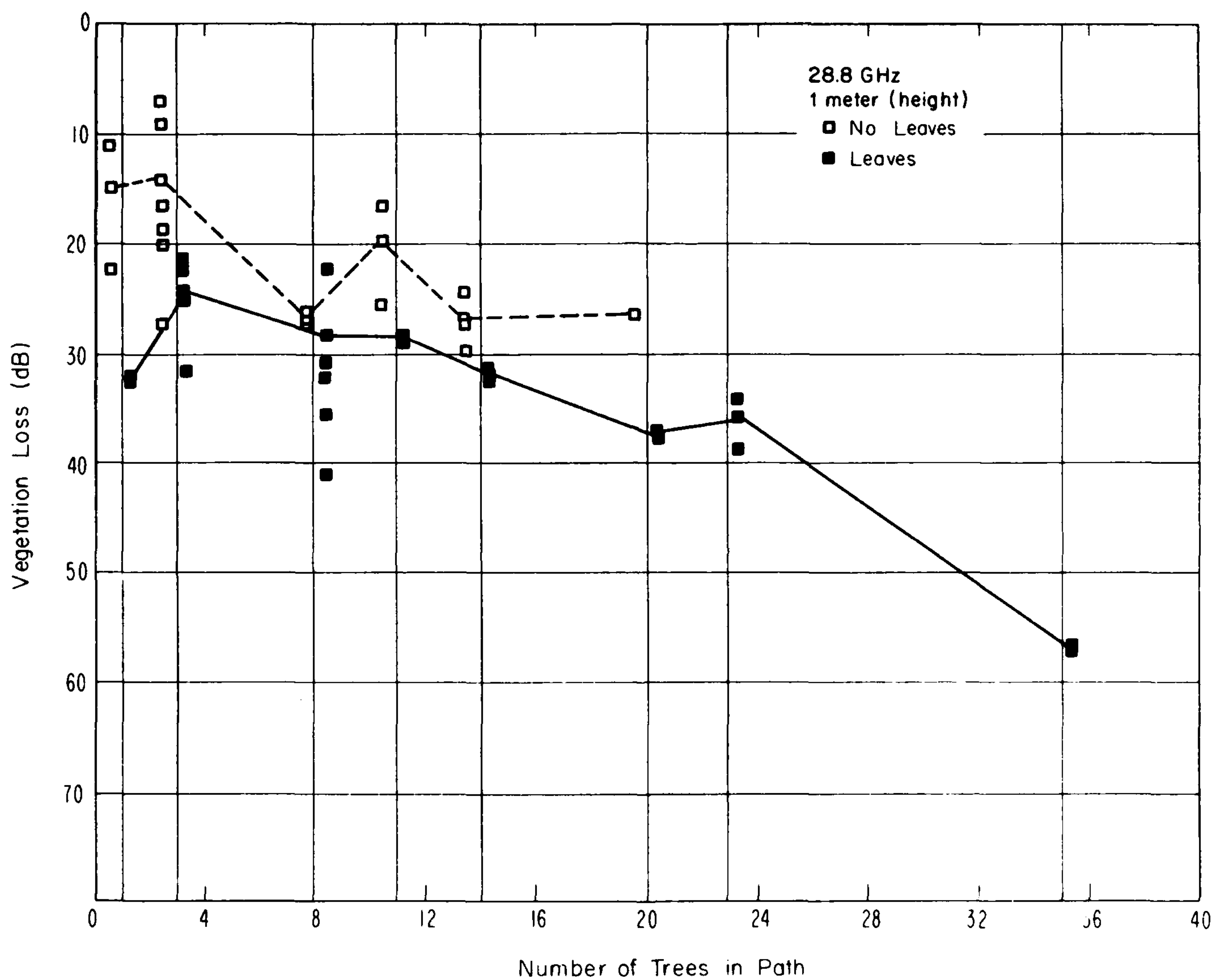

Fig. 4.2. Vegetation loss as a function of the number of trees in path for 28.8 GHz at 1 meter.

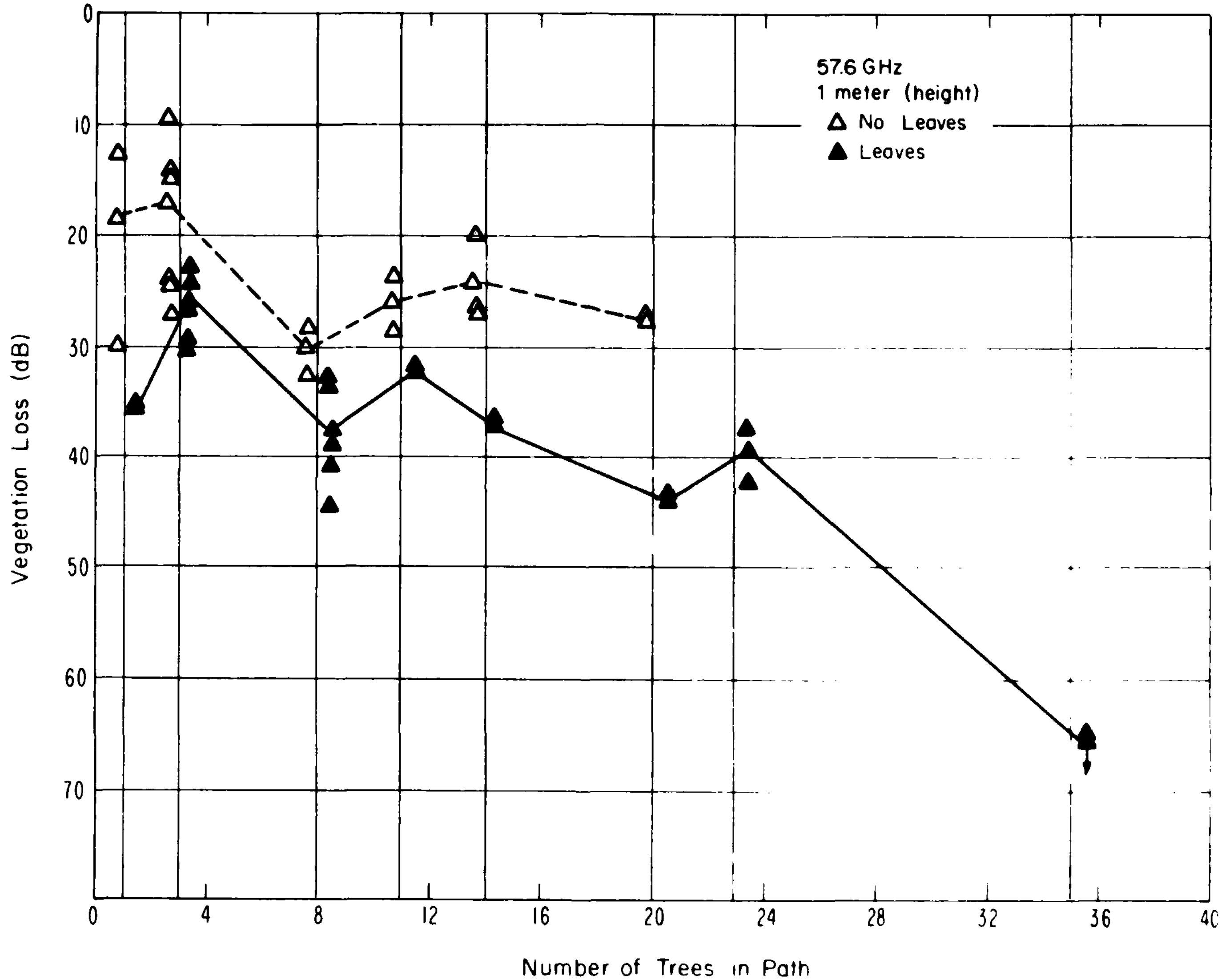

Fig. 4.3. Vegetation loss as a function of the number of trees in path for 57.6 GHz at 1 meter.

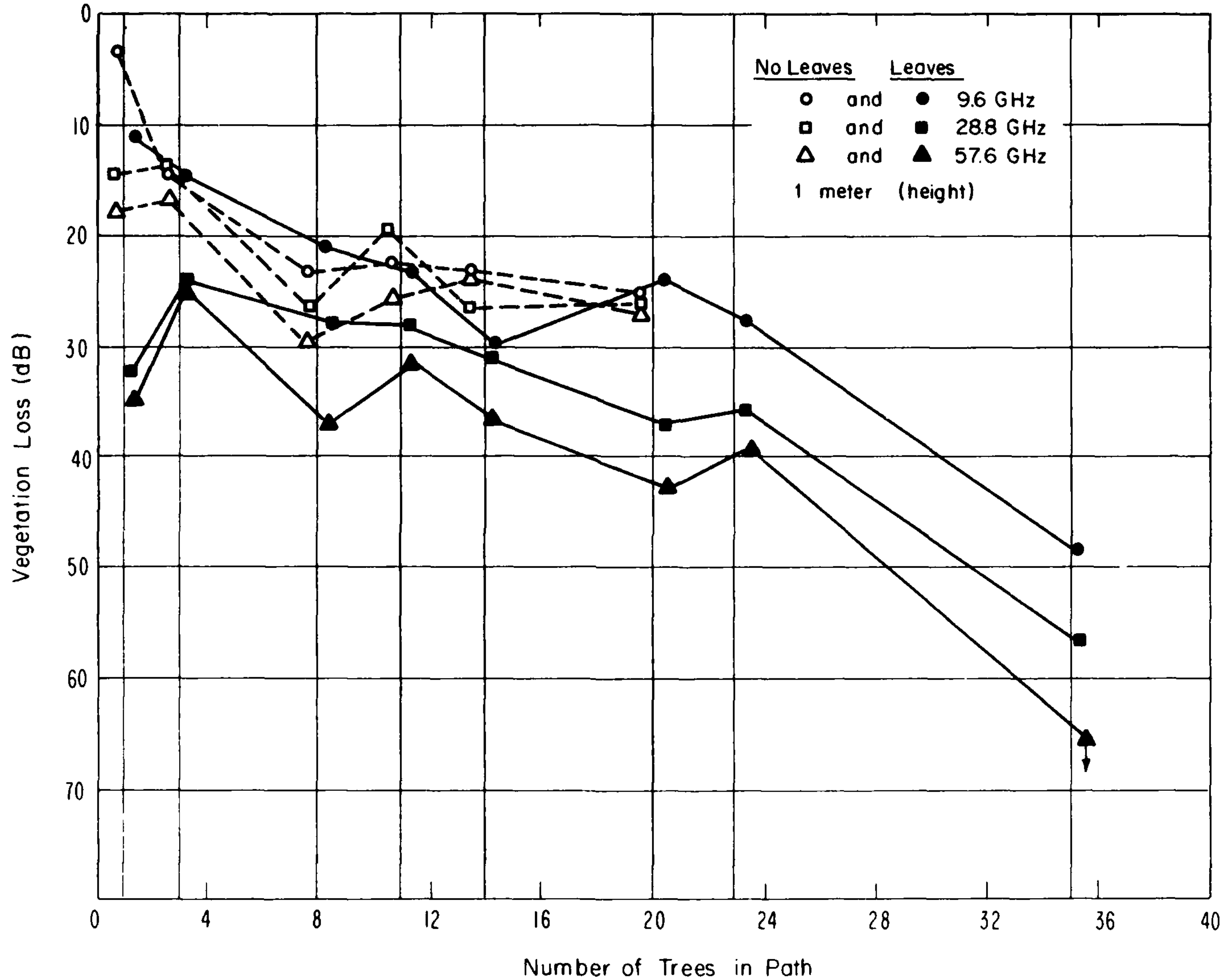

Fig. 4.4. Average values of vegetation loss as a function of the number of trees on path for 9.6, 28.8, and 57.6 GHz at 1 meter.

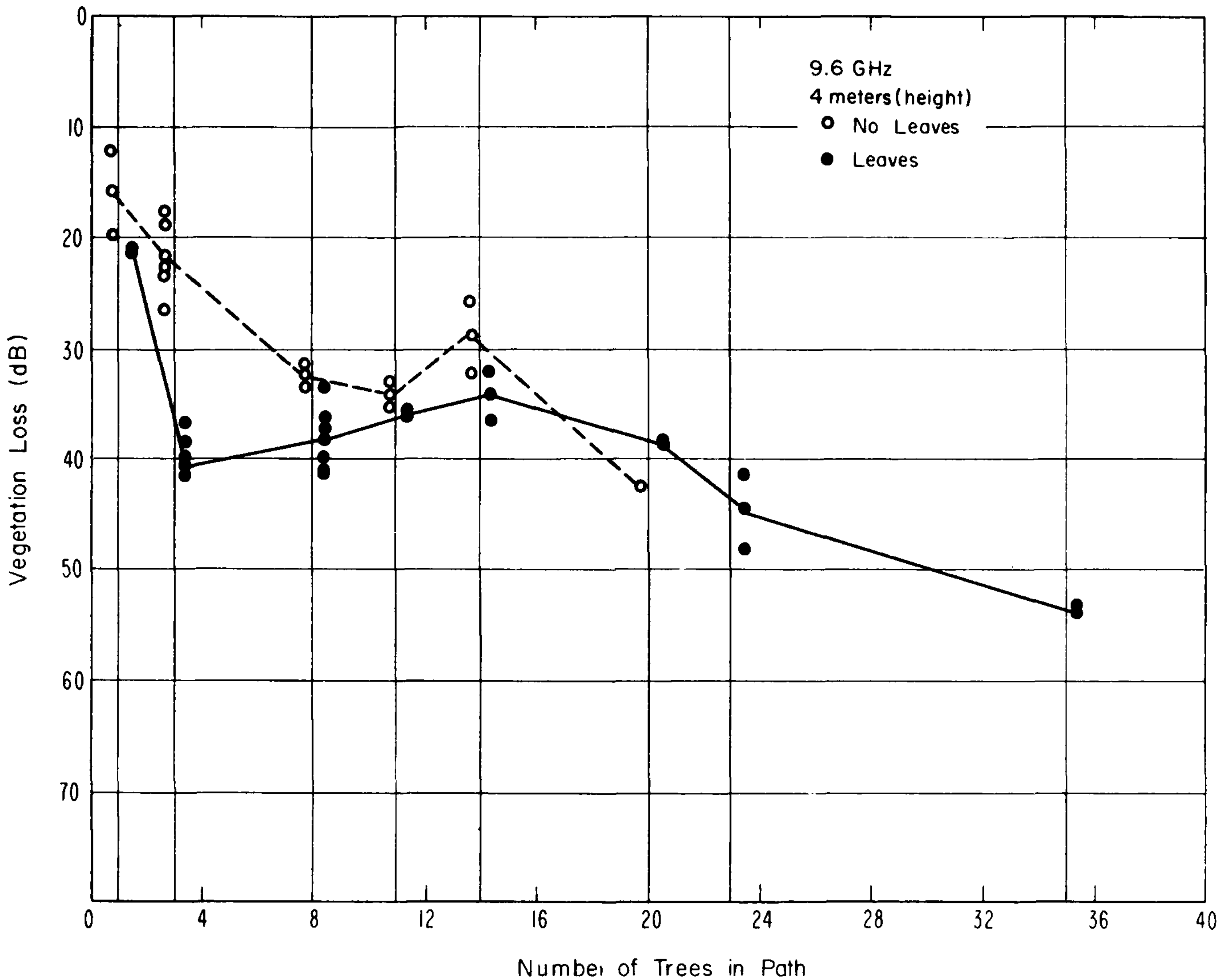

Fig. 4.5. Vegetation loss as a function of the number of trees in path for 9.6 GHz at 4 meters.

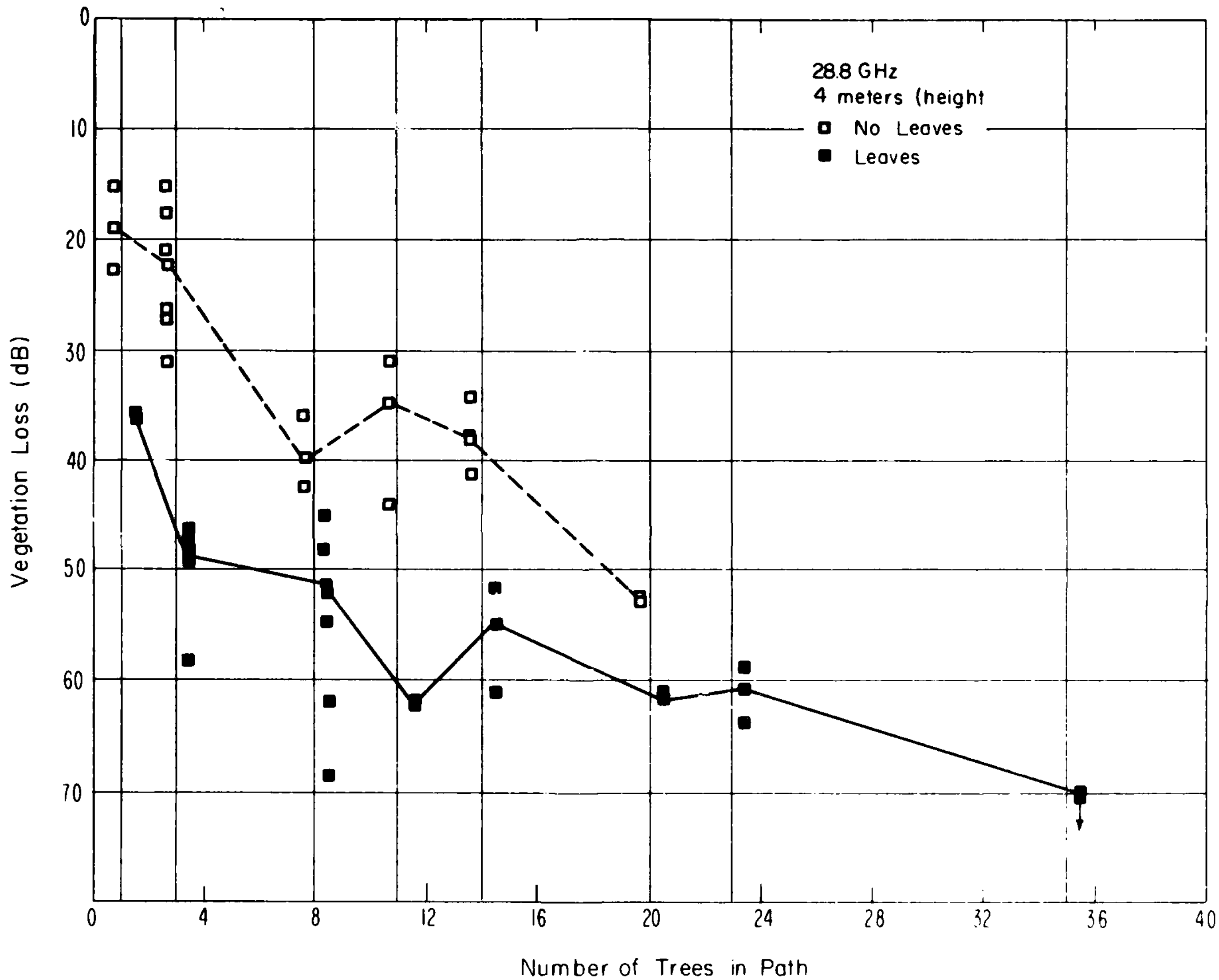

Fig. 4.6. Vegetation loss as a function of the number of trees in path for 28.8 GHz at 4 meters.

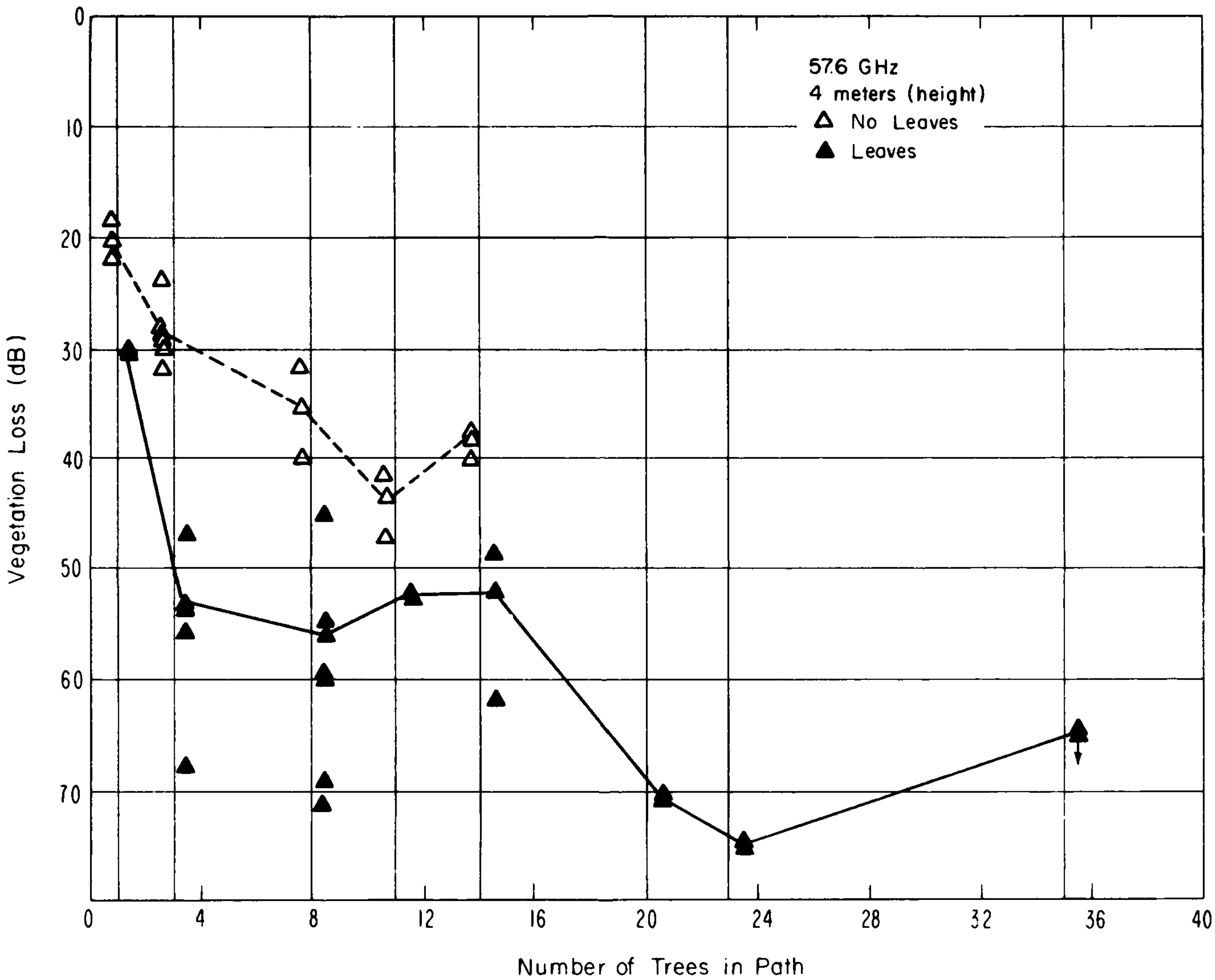

Fig. 4.7. Vegetation loss as a function of the number of trees in path for 57.6 GHz at 4 meters.

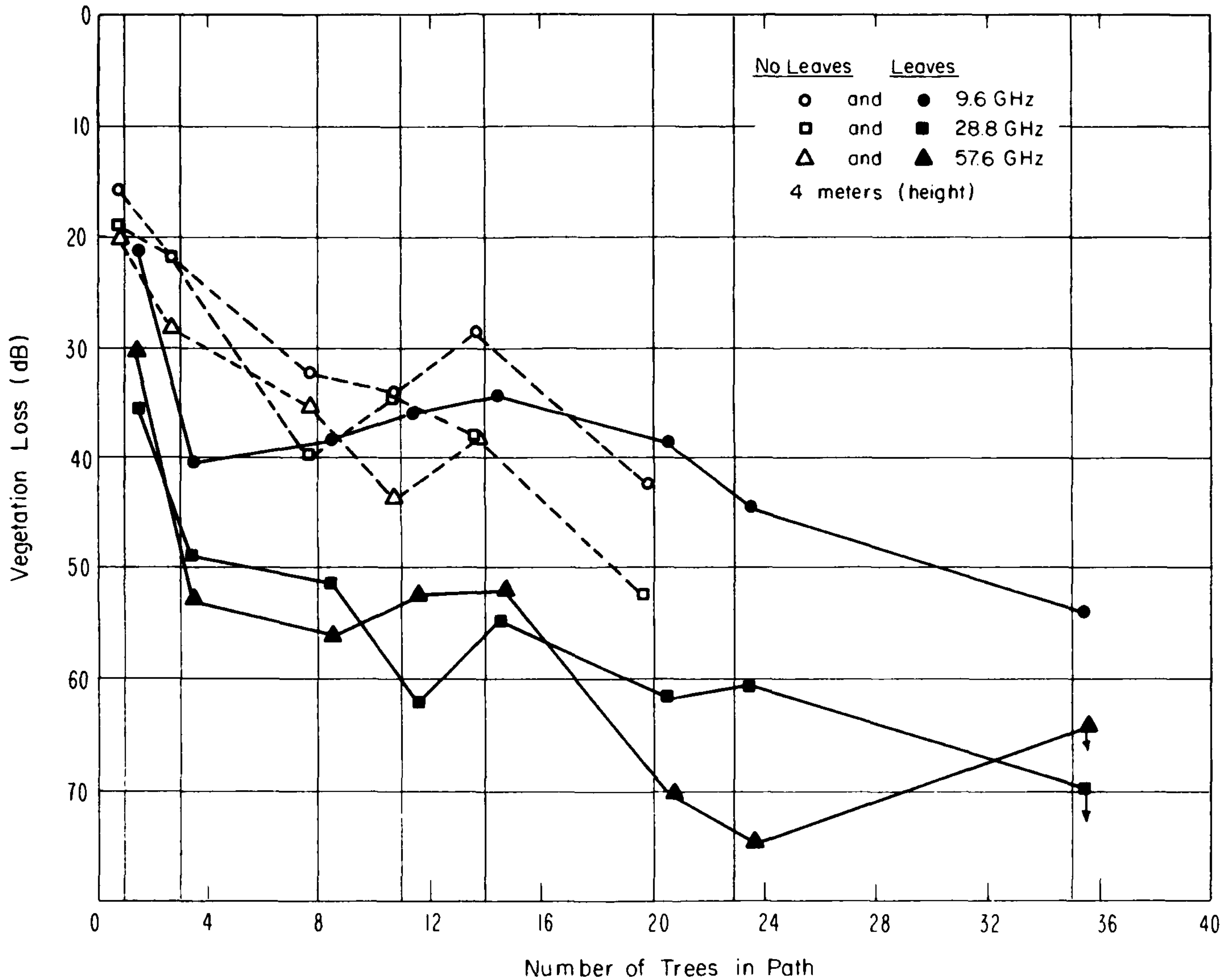

Fig. 4.8. Average values of vegetation loss as a function of the number of trees in path for 9.6, 28.8, and 57.6 GHz at 4 meters.

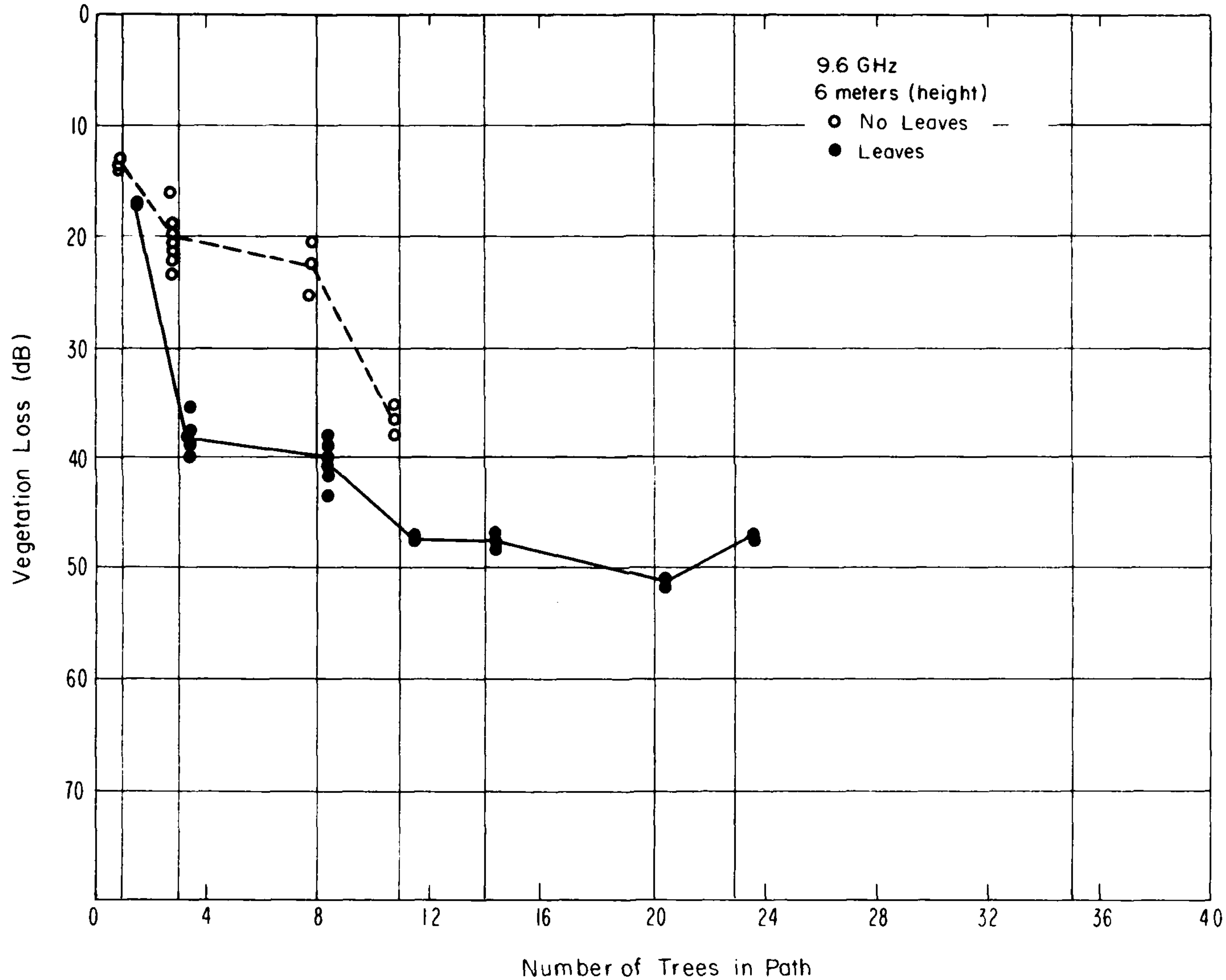

Fig. 4.9. Vegetation loss as a function of the number of trees in path for 9.6 GHz at 6 meters.

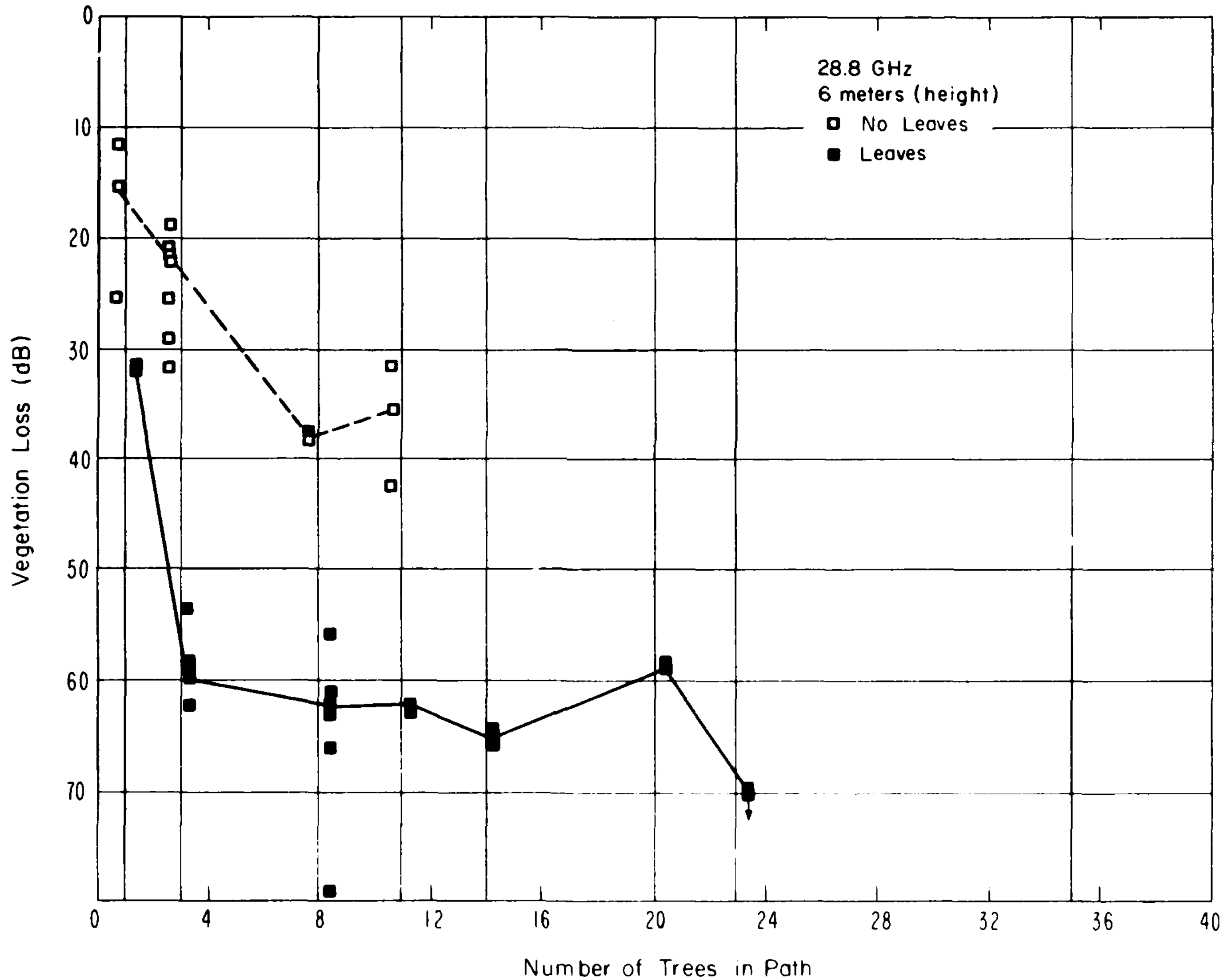

Fig. 4.10. Vegetation loss as a function of the number of trees in path for 28.3 GHz at 6 meters.

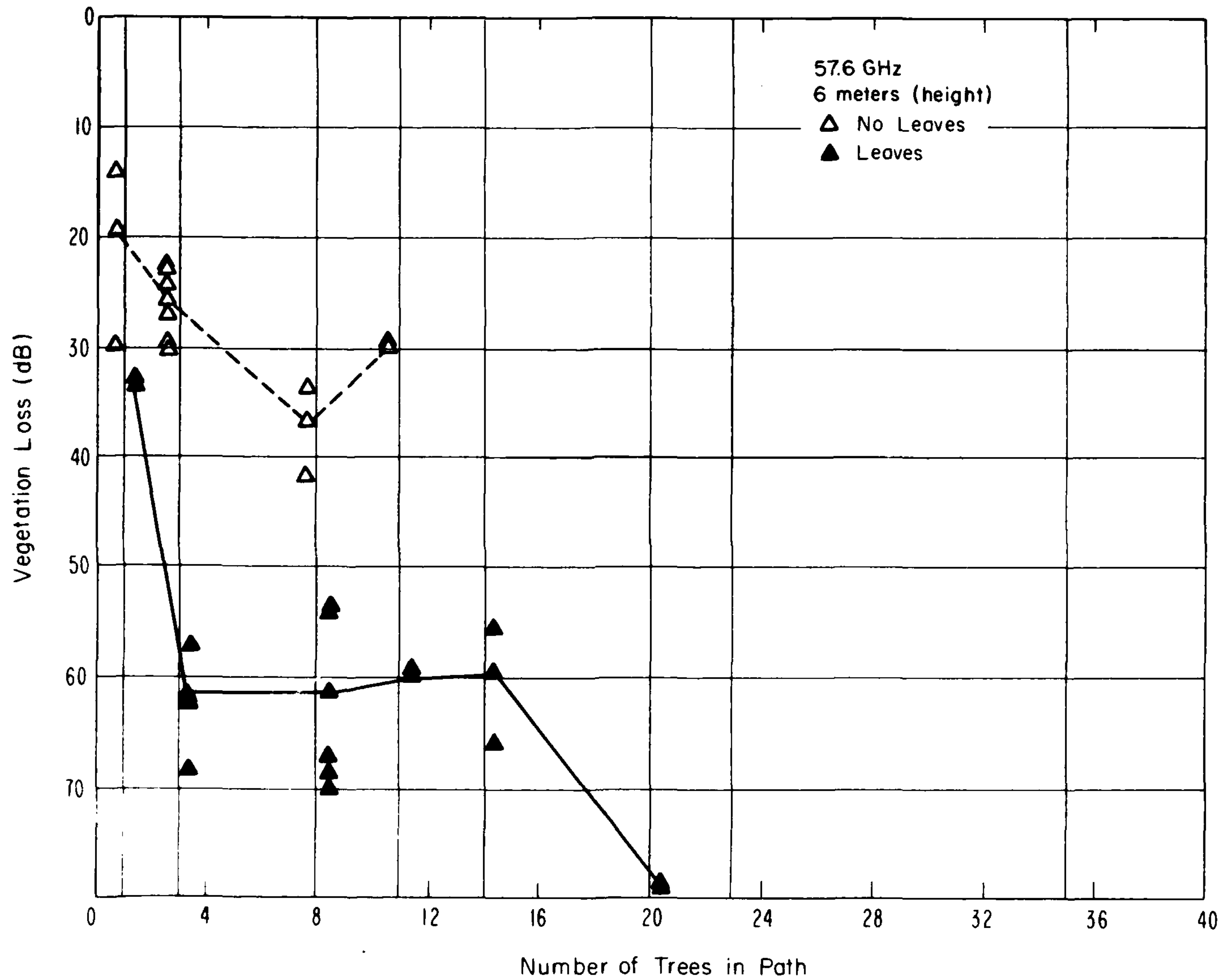

Fig. 4.11. Vegetation loss as a function of the number of trees in path for 57.6 GHz at 6 meters.

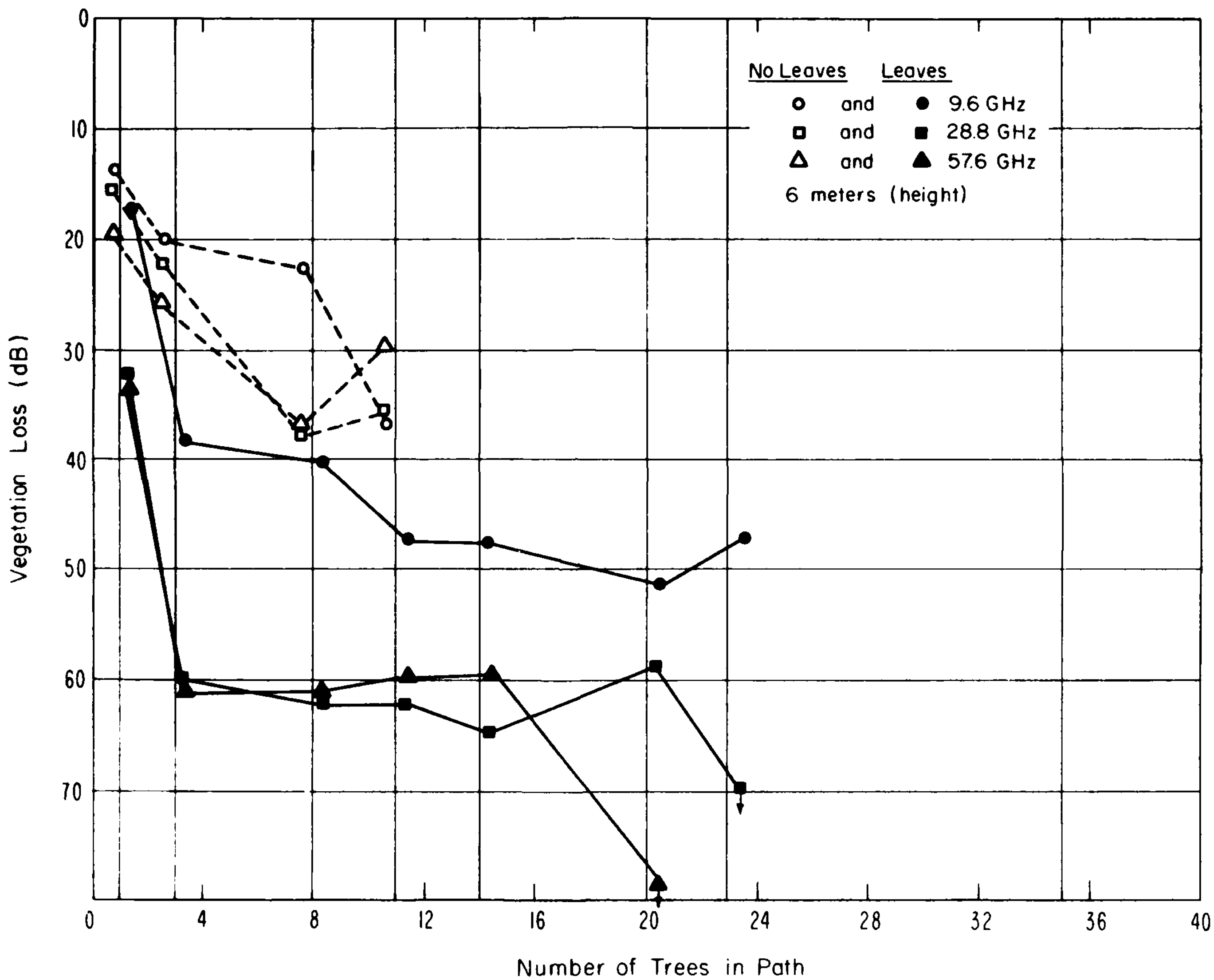

Fig. 4.12. Average values of vegetation loss as a function of the number of trees in path for 9.6, 28.8, and 57.6 GHz at 6 meters.

With no leaves, the small twigs and branches absorb the electromagnetic waves at a low rate, so that multiple diffraction does not become the dominant mode of propagation until after several trees. Therefore, it is multiple diffraction from the large number of scattering objects that define the lower loss propagation mode. With leaves, there is a much higher attenuation per unit volume so the transition takes place with fewer trees in the path but at a much greater loss.

Without leaves, there was not a consistent dependence of loss with frequency, but with leaves, the higher two frequencies showed much higher losses than 9.6 GHz. The loss at 28.8 and 57.6 GHz appeared to be very nearly the same.

In Figure 4.12, the data at the 6 meter height show very similar loss characteristics as a function of number of trees as the 4 meter height data except the span of the trees at this height was somewhat greater producing greater losses. The 28.8 and 57.6 GHz data has the break in the curve at 8 trees for the no leaves state; however, only one additional point at 11 trees was measured so the trend can not be confirmed beyond this number. With leaves, the break in the curve at 3 trees is even more abrupt than at the 4 meter height. Again the 28.8 and 57.6 GHz data show about the same loss, considerable more than at 9.6 GHz.

Table 4.1 is included to provide an indication of the order of magnitude of difference between the leaf and no leaf conditions at the three heights and frequencies for which measurements were made. These values are averages for all paths where comparative measurements were made regardless of the number of trees on path. The table tends to highlight the effect of the presence of leaves. The most significant fact is the spread in loss between 9.6 GHz and the upper frequencies and the closeness of the 28.8 and 57.6 GHz values.

TABLE 4.1

Vegetation loss (dB) as a differential value between trees in leaf and trees without leaves

Height (m)	Frequency (GHz) 9.6	28.8	57.6
1	2.8	10.1	12.6
4	8.9	22.6	22.7
6	14.3	29.1	29.6

The data in Figures 4.4, 4.8, and 4.12 were processed to find the loss in dB per tree as a function of the number of trees in the path and presented in Figures 4.13, 4.14, and 4.15, respectively. In these Figures, the vertical scale is vegetation loss in dB per tree and the horizontal scale is number of trees on path. These curves show a nearly constant loss per tree after the number of trees on path exceeds eight. In the next section, these data are given as a function of foliage depth for the 4 and 6 meter heights.

B. Loss vs. Foliage Depth

Selected data from the previous section are presented in this section not as a function of the number of trees on the path, but as a function of depth of foliage. Only data measured when the trees were in leaf is included. The data for the 4 and 6 meter heights are presented in Figures 4.16, 4.17, and 4.18 for 9.6, 28.8, and 57.6 GHz, respectively. The 1 meter height data was not included because of the nonuniform foliage at that height. To convert from trees on path to the depth of foliage in meters, an estimate (based on measurement of a number of trees) was made of average depth per tree at the 4 meter and 6 meter heights. Nine meters per tree was used for the 4 meter height and 11 meters per tree was used for the 6 meter height. The vegetation losses measured at 4 meters are less (on the average) than the vegetation losses measured at 6 meters. This difference might be attributable to the branch structure and/or the leaf population per meter at these heights. Or the difference may be due to a miscalculation of the average depth of foliage per tree along the actual path, or a combination of these.

Curves showing predicted values in these figures come from a modified exponential decay model described in "An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Trees," Report No. ESD TR-81-101[2]. The most significant difference between the measured and predicted data is the point at which the slope changes. The predicted curve is straight and steep to a depth of 14 meters. From 14 meters to 400 meters the slope is still steep but the roll-off is exponential. As can be seen in the figures, the measured data has a steep slope to about 30 meters and then has a considerably more shallow-slope to the extent of measurements. The lack of uniform data samples in the 20 to 80 meter range prohibits a more precise statement concerning the break in the curve using the measured data.

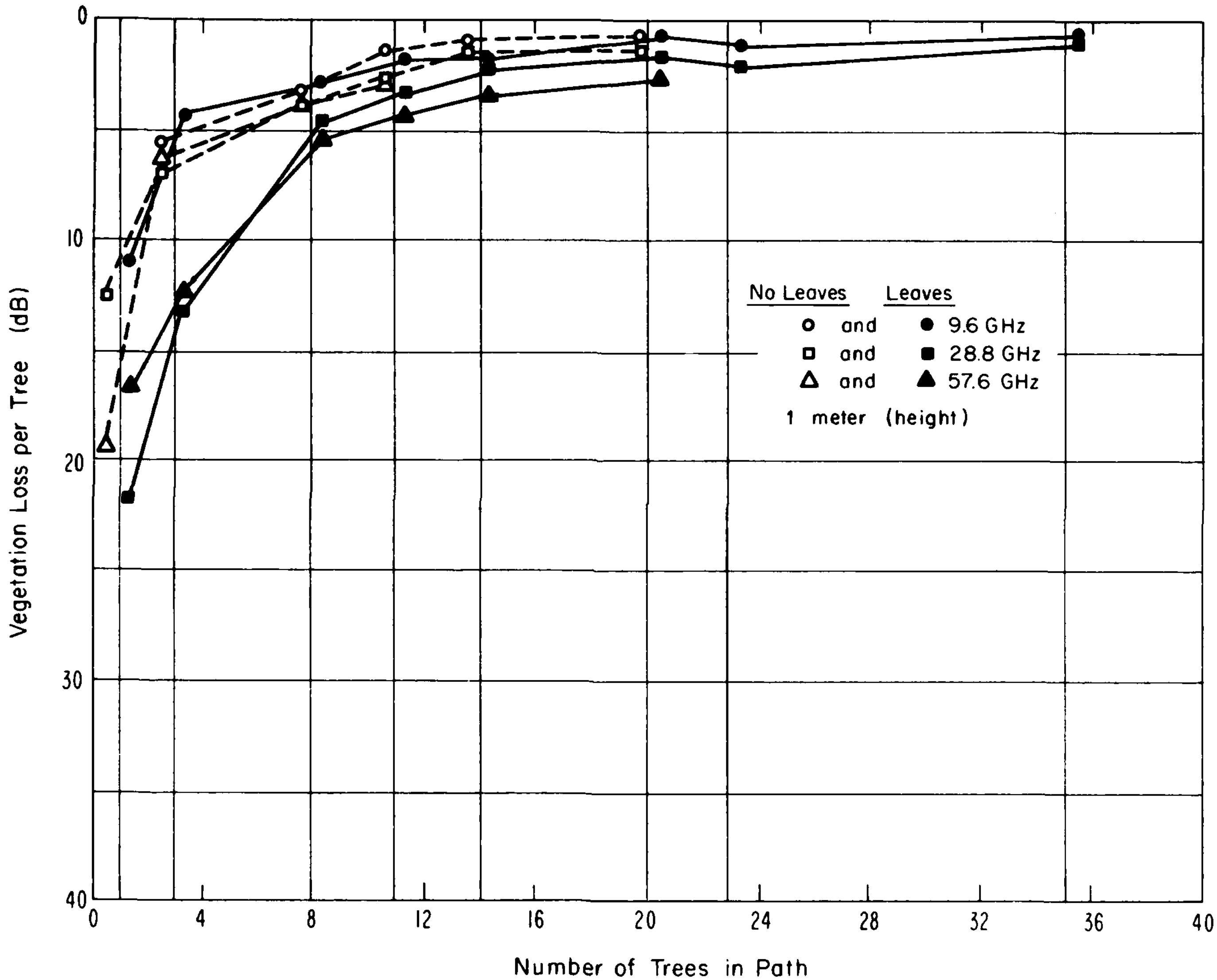

Fig. 4.13. Average values of vegetation loss per tree as a function of the number of trees in path at 9.6, 28.8, and 57.6 GHz at 1 meter.

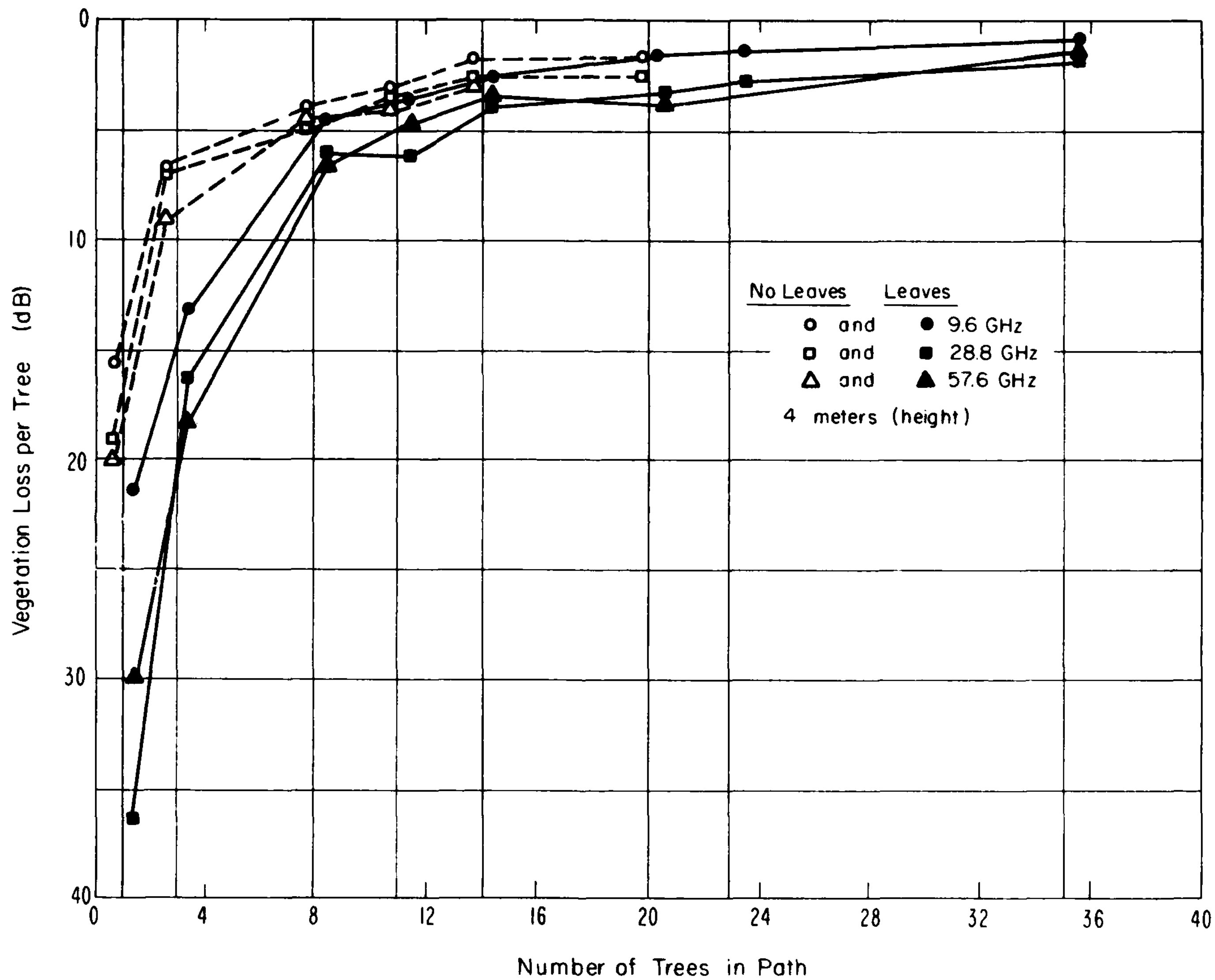

Fig. 4.14. Average values of vegetation loss per tree as a function of the number of trees in path at 9.6, 28.8, and 57.6 GHz at 4 meters.

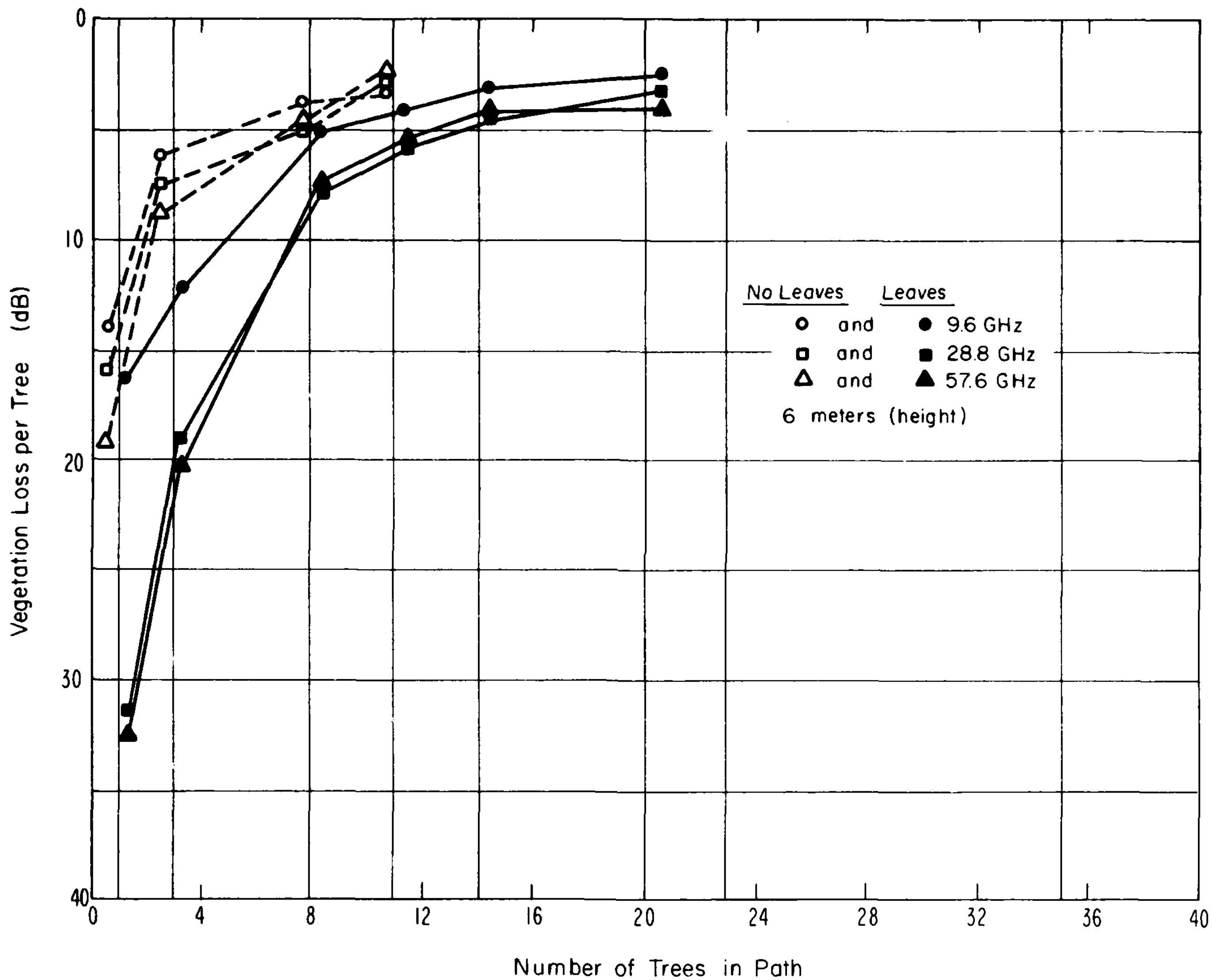

Fig. 4.15. Average values of vegetation loss per tree as a function of the number of trees in path at 9.6, 28.8, and 57.6 GHz at 6 meters.

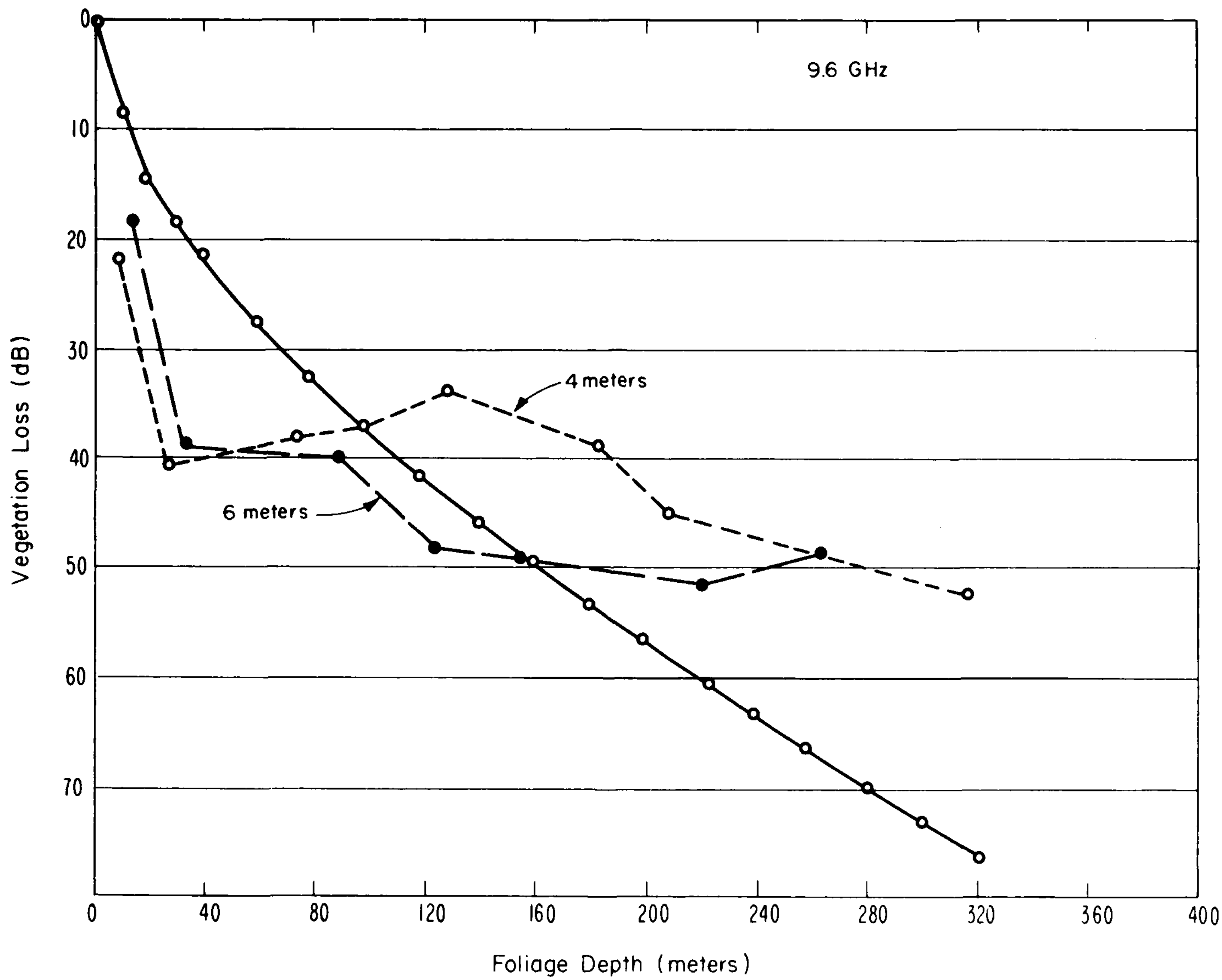

Fig. 4.16. Measured and predicted values of vegetation loss as a function of foliage depth for 9.6 GHz.

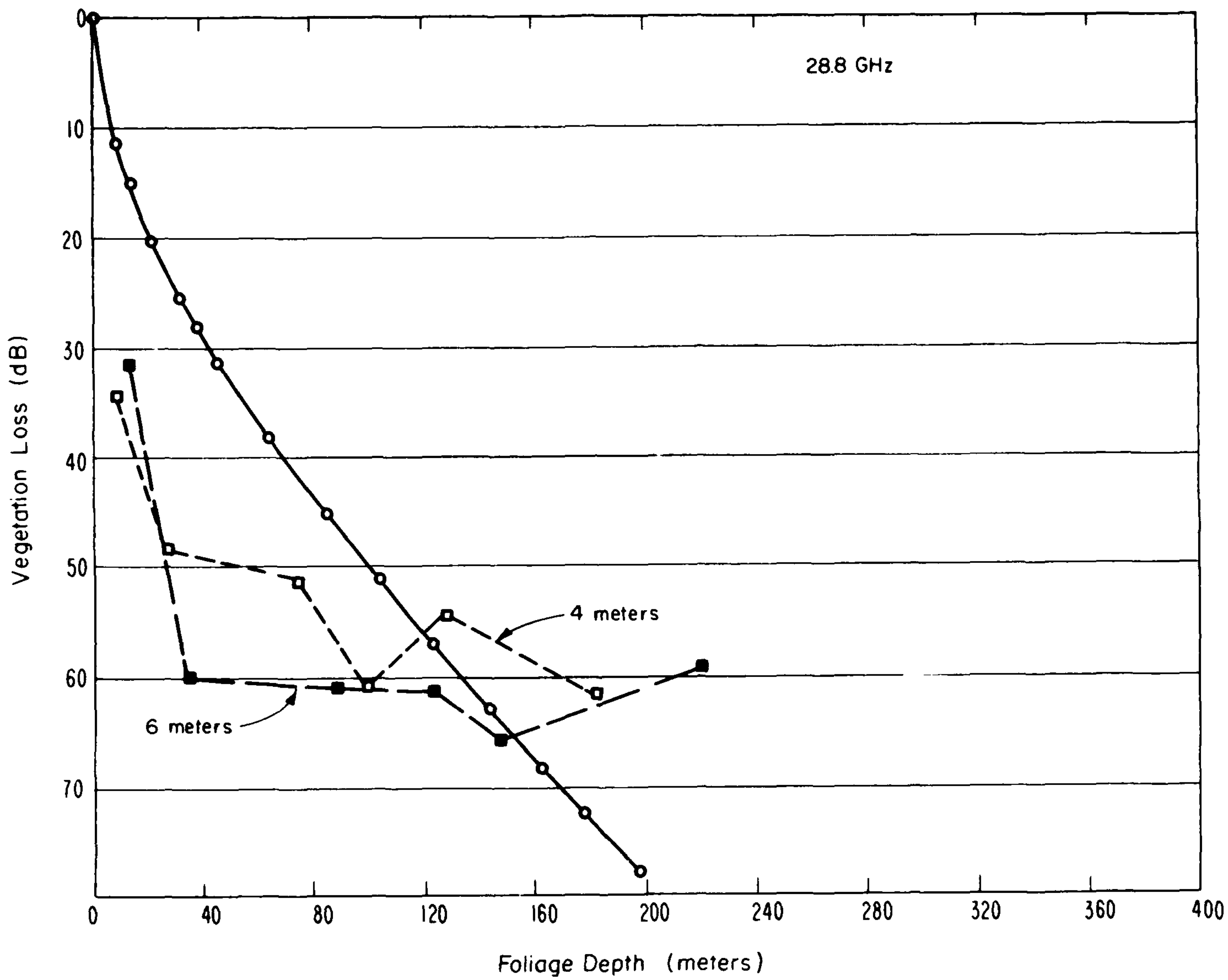

Fig. 4.17. Measured and predicted values of vegetation loss as a function of foliage depth for 28.8 GHz.

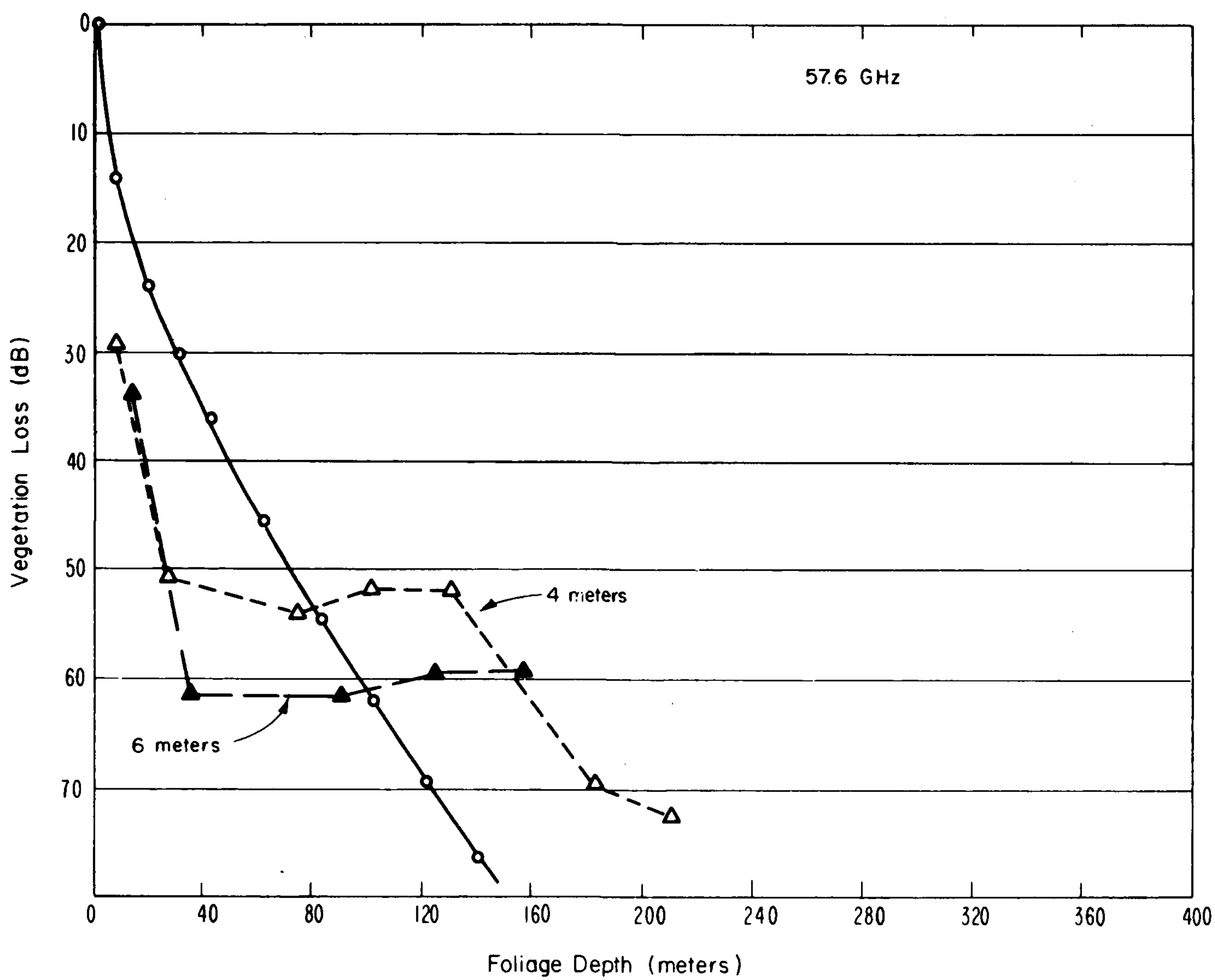

Fig. 4.18. Measured and predicted values of vegetation loss as a function of foliage depth for 57.6 GHz.

C. Azimuth and Elevation Angle Scans

Because of the propagation mode that occurred when diffraction scattering appeared to be dominant, the directional properties of the arriving signals are most interesting. A series of azimuth and elevation angle scans are presented for all three frequencies, the three terminal heights, and both leaves and no leaves states at tree depths of 1, 3, 8, and 11 trees; showing how the signal angle of arrival varies with tree depth. Figures 4.19 through 4.21 show antenna scans with no leaves and Figures 4.22 through 4.24 show antenna scans with leaves. An unobstructed reference scan is superimposed (the light trace) on each of the data scans in these figures. The reference antenna patterns used were with VV polarization, taken on a 300 meter path at a one meter height. The height over ground for the unobstructed antenna patterns affects the elevation plots slightly as the ground reflection produces a multipath signal[1]. The effect is least at the 1 meter height and tends to broaden the main lobe on the side where the receiving antenna points toward the ground.

Figure 4.19 shows the antenna scans for a no-leaf state at a 1 meter height. The main feature of these plots is that the maximum signal typically arrives at one side or the other of the main lobe of the azimuth reference scans, particularly at the higher frequencies. Since the plots for vegetation loss of the previous section used the maximum signal levels observed on either the azimuth or elevation angle scan, it should be emphasized that much greater losses occur in many of these scans. For example, in Figure 4.19 for 8 trees in the 28.8 and 57.6 GHz azimuthal scans, the signal levels under the main lobe drop to a -50 or -60 dB. These maximum losses are significantly smaller than the maximum received signals of -25 to -30 dB.

Figure 4.22 shows the azimuthal and elevation angle scans at 1 meter terminal height for 1, 3, 8, and 11 trees with leaves. The azimuthal scans show similar results as for the no-leaf state; that is, the maximum signals occurring off the center beam. At the 11-tree depth, however, the signal amplitude is as high at the center beam as the off-center level. The reason again is likely the complexity of the path and the variability of the geometry in that the trunks may not be perfectly aligned or of uniform size.

Azimuth and elevation angle scans at the 4 meter height without leaves, Figure 4.20, show a gradual loss of signal directivity, with increasing tree depth and at the 11-tree depth, the signal level is nearly flat over all scans. For the foliated state at 4 meters, Figure 4.23, the flattening out of the signal level occurs at the 8-tree depth. This suggests that the energy is scattered nearly equally

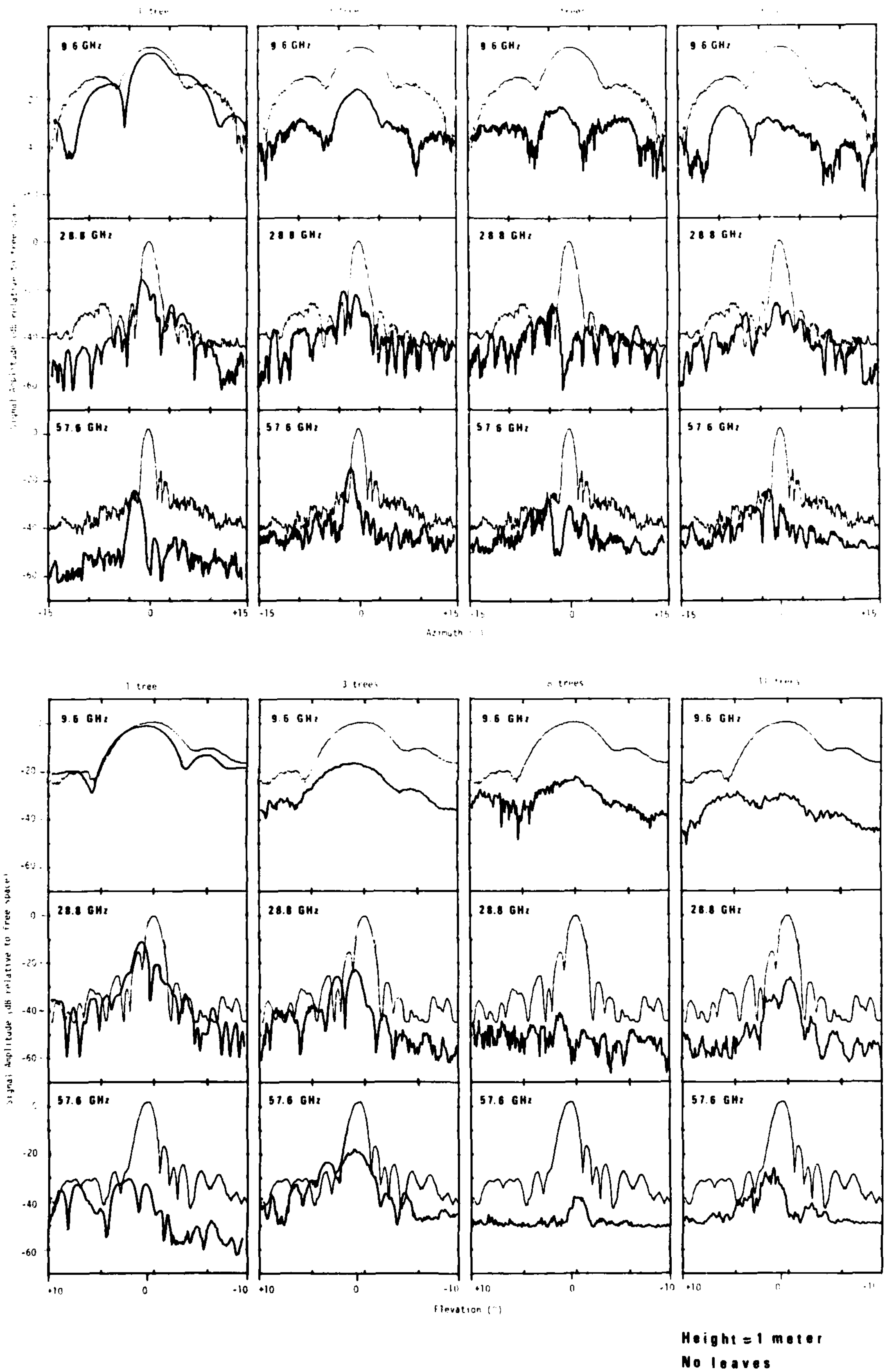

Fig. 4.19. Azimuthal and elevation angle scans at the 1 meter height for 1, 3, 8, and 11 trees without leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

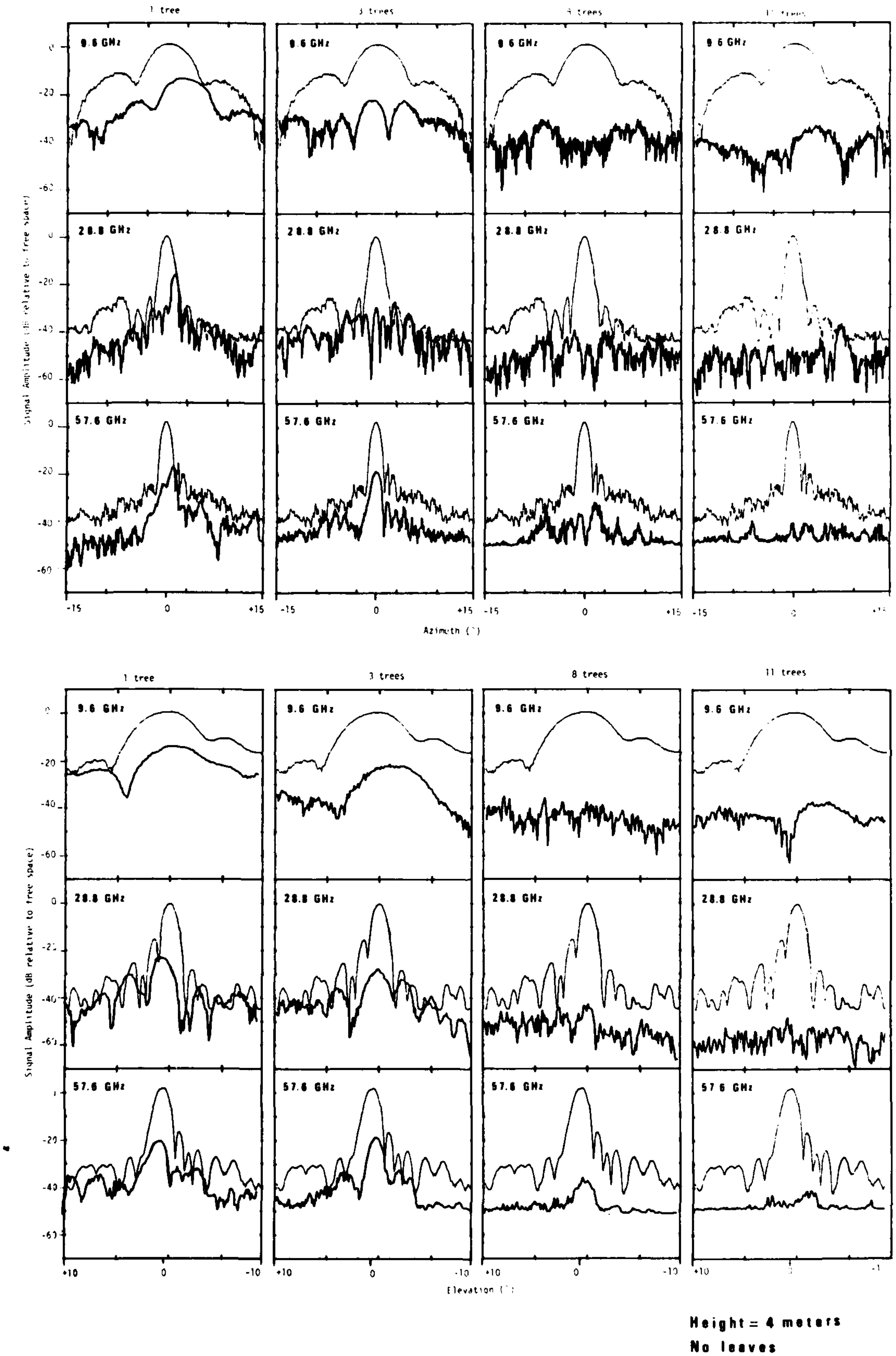

Fig. 4.20. Azimuthal and elevation angle scans at the 4 meter height for 1, 3, 8, and 11 trees without leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

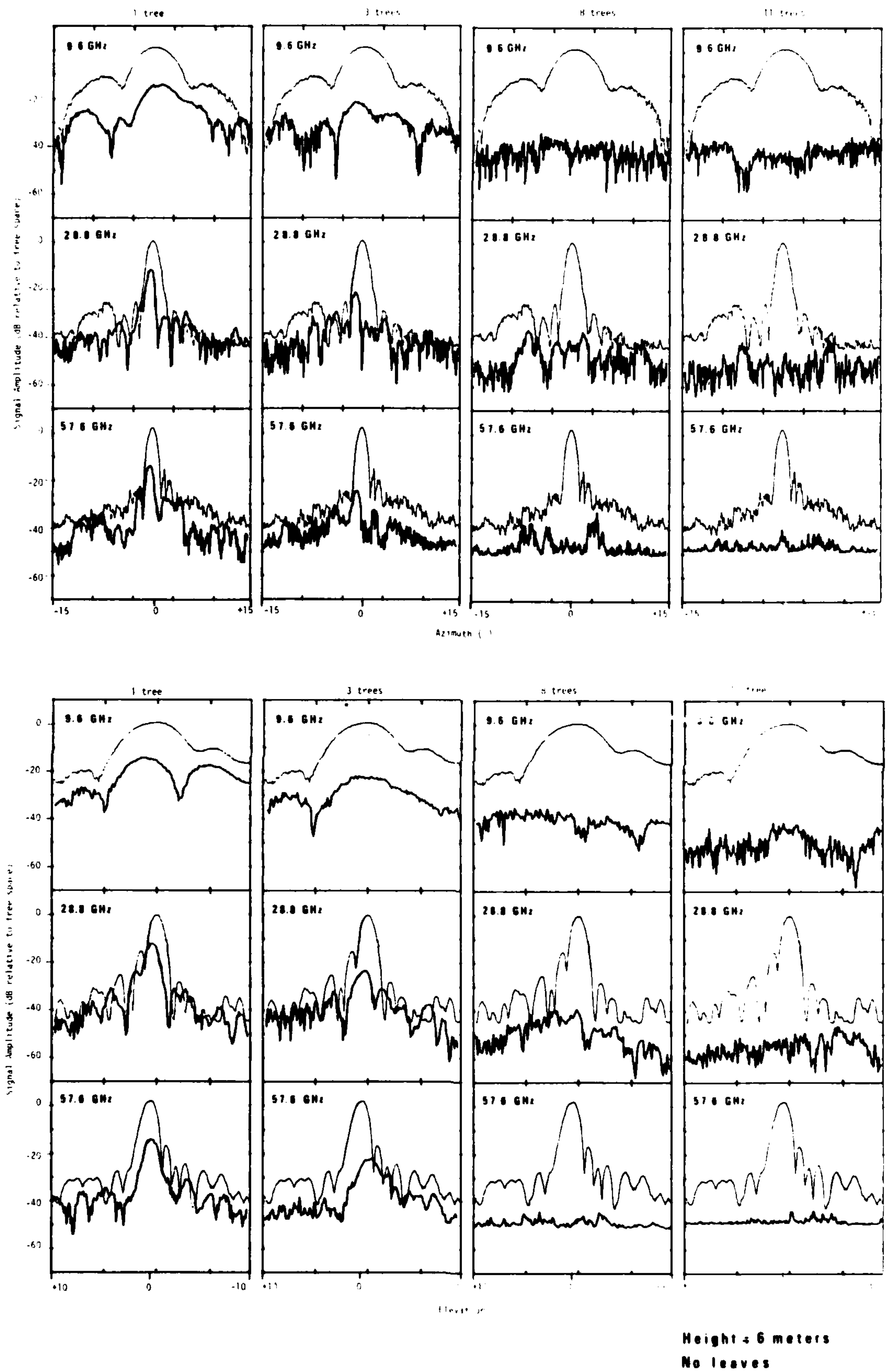

Fig. 4.21. Azimuthal and elevation angle scans at the 6 meter height for 1, 3, 8, and 11 trees without leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

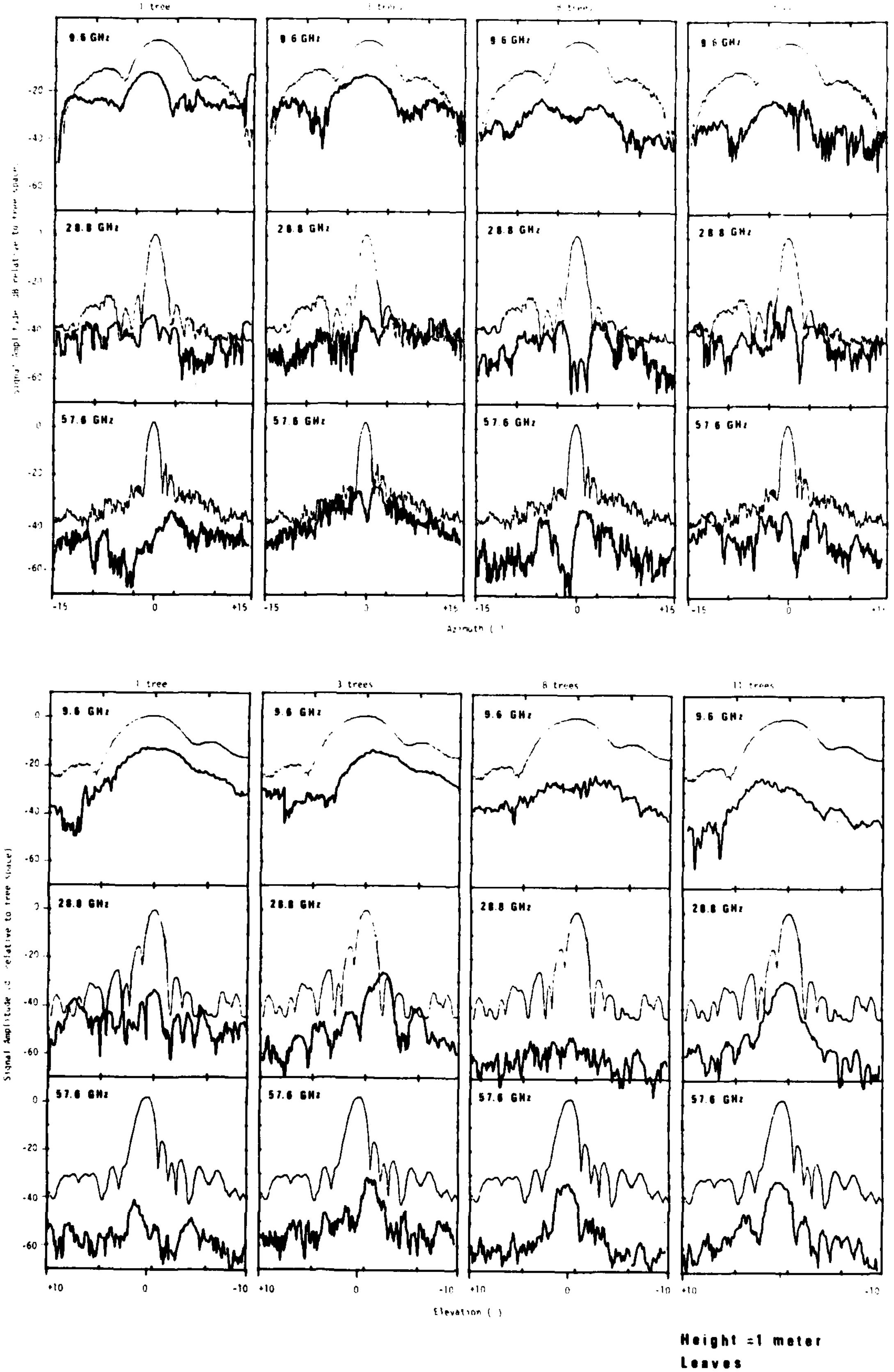

Fig. 4.22. Azimuthal and elevation angle scans at the 1 meter height for 1, 3, 8, and 11 trees with leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

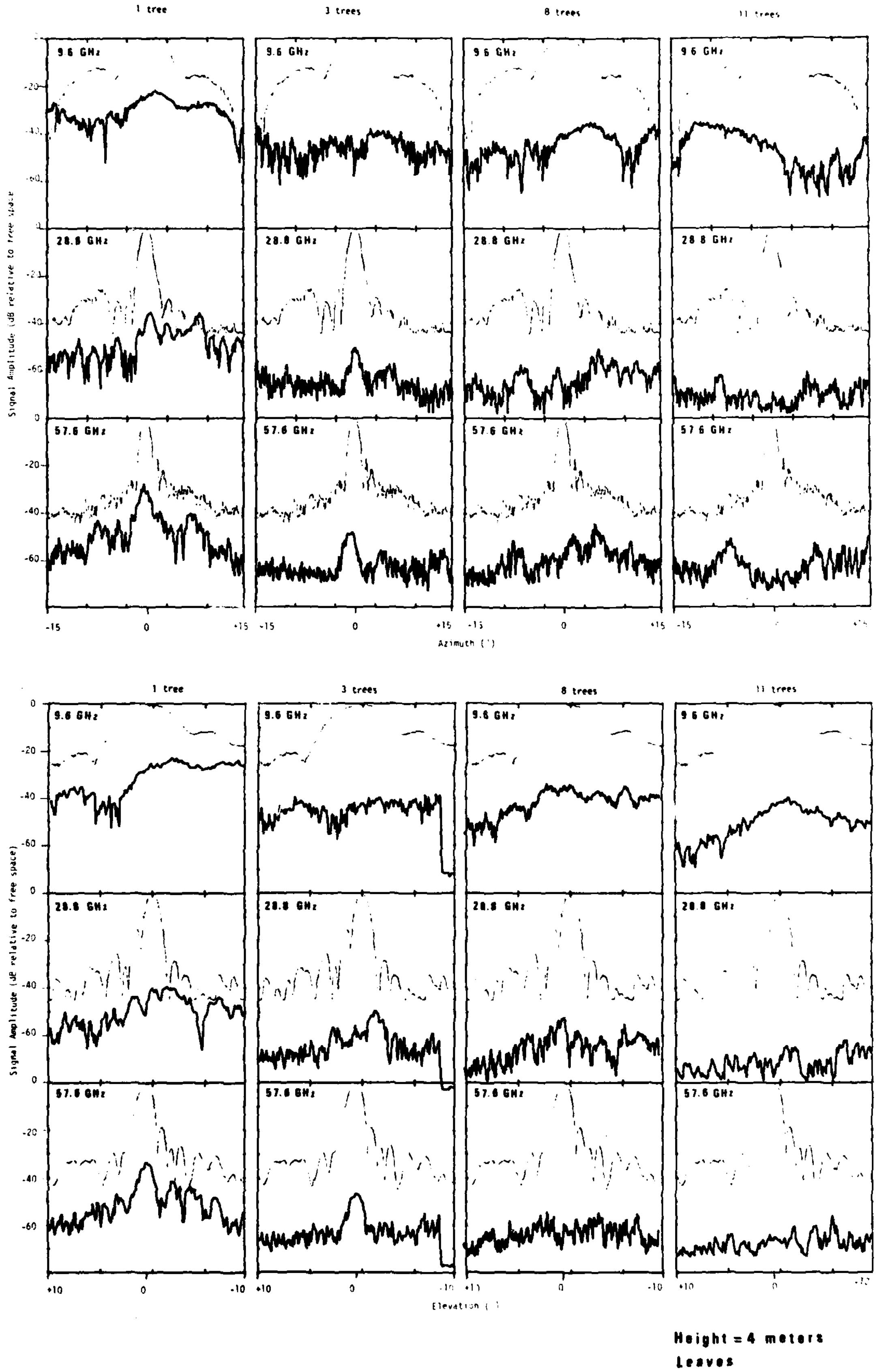

Fig. 4.23. Azimuthal and elevation angle scans at the 4 meter height for 1, 3, 8, and 11 trees with leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

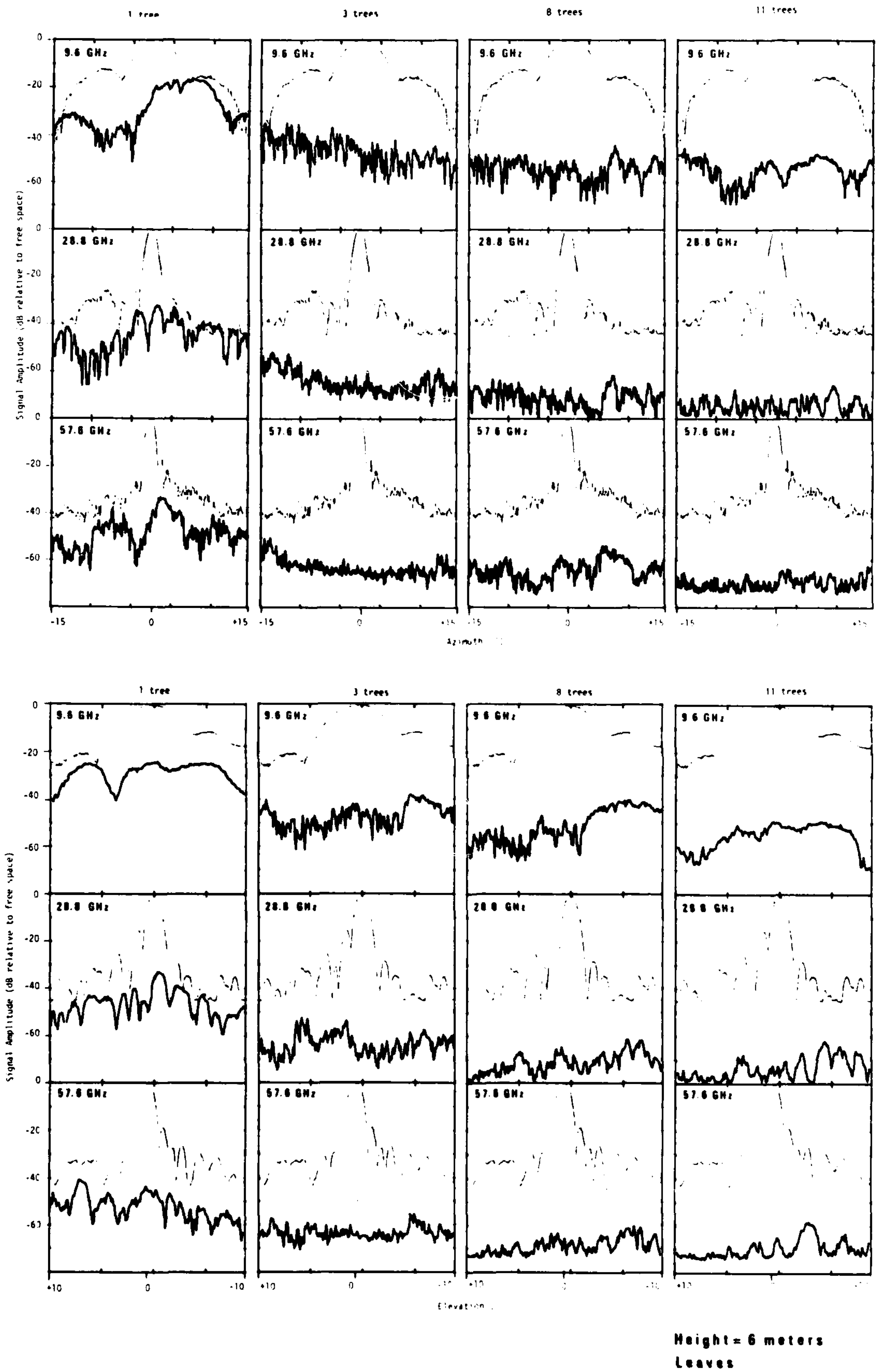

Fig. 4.24. Azimuthal and elevation angle scans at the 6 meter height for 1, 3, 8, and 11 trees with leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

from the entire tree. At the 4 meter level, the receiving antenna is generally 2 to 4 meters from the branches, but 12 to 14 meters from the trunk of the last tree on the path. The $\pm$ 15 degree azimuth scans illuminate nearly the full width of the tree except some branches may be partially obscure at the extreme outer edge. The elevation scan at +10 degrees almost illuminates the highest branches of the closest tree to the receiving antenna at the 4 meter height and passes through many layers of branches before intersecting the ground at the -10 degree pointing. This estimate of the pointing geometry is included to point out that no over-the-top or down-the-row mode of propagation was detected.

The tree span was greatest at the 6 meter height, so the plots for this height contained in Figure 4.21 for no leaves and Figure 4.24 with leaves show the highest signal loss. The result of this increased foliage depth is that the signal directivity flattened out by 8 trees for the no-leaf state and by 3 trees with leaves. At the 6 meter height, the tree top is fully illuminated and still no over the top mode is apparent.

D. Horizontal Scans of the Orchard

The vegetation loss characteristics discussed in sections A, B, and C were determined from measurements with a row of trees directly on the propagation path. In this section, the measurements were made by moving the transmitter along an arc at the edge of the orchard. This measurement technique provides a uniform path length, but with continual variation in tree density and tree position relative to the propagation path. These tests give some assessment of propagation characteristics for a continuous family of paths through a segment of the orchard at trunk level. Transmitter sites TM_1 and TM_2 are shown in Figure 3.3. These are the arc segments over which the transmitter was moved. Tests were made using both TM_1 and TM_2 while the trees were without leaves and at TM_1 only when leaves were on the trees.

The data in Figure 4.25 was recorded in April (defoliated state) while the transmitter traversed from A to B and the receiver was located at R_{13}, Figure 3.3. Receiver site R_{13} is situated between two rows of trees such that a line-of-sight path exists between the receiver and the transmitter when located near mid-path of TM_1. This was a 720 meter path. While the transmitter moved from A to B, the receiving antennas were manually positioned to track the transmitter position. This configuration created a line-of-sight, unobstructed path as the transmitter moved from approximately -6 meters to +6 meters and the near 0 dB signal level in this

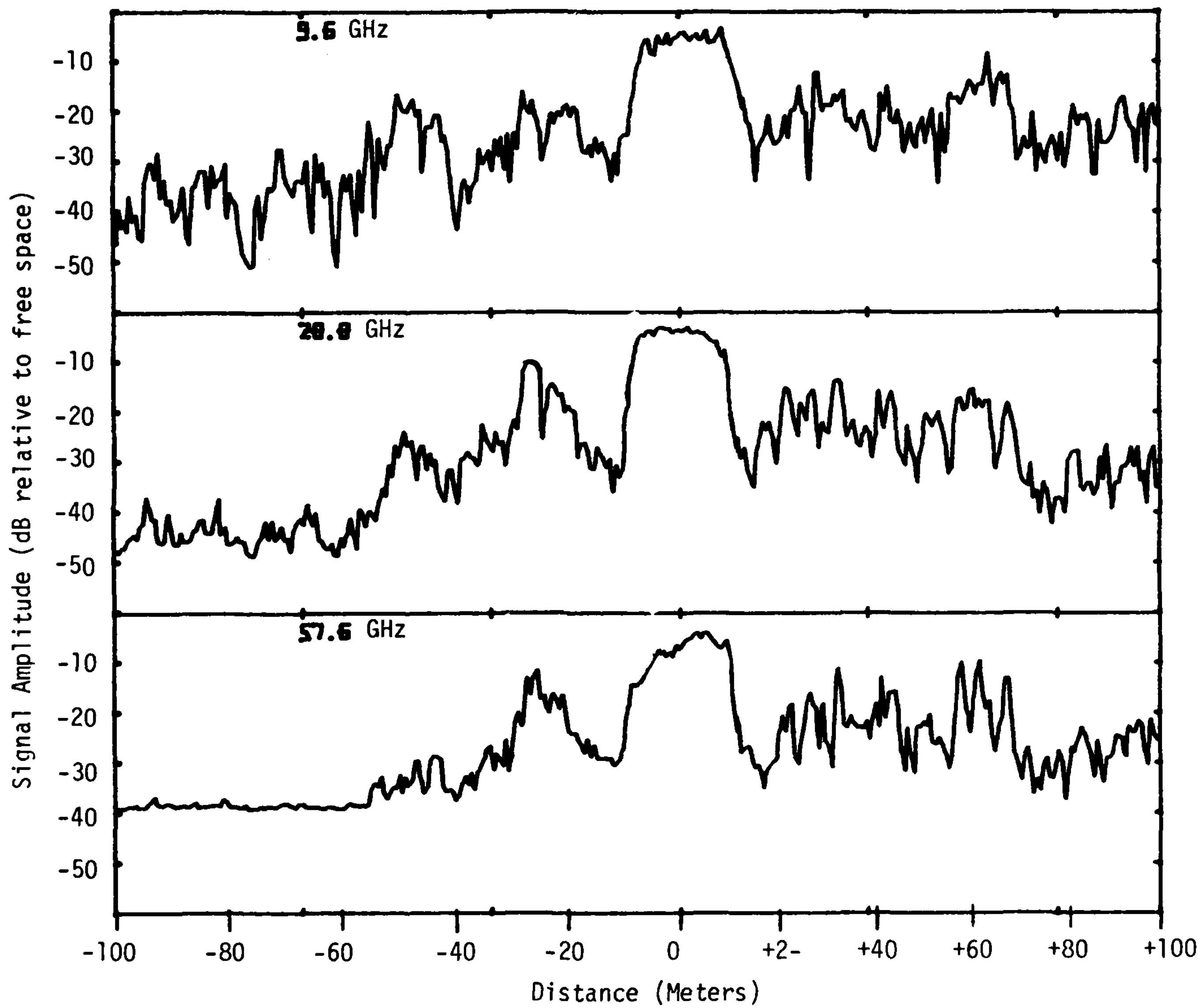

Fig. 4.25. Received signal amplitude as a function of scan listance on a 720 meter propagation path (April 1982).

segment reflects that condition. Those portions of each trace outside the unobstructed sector show the received signal after propagating through a varying number of trees in the path. Over most of the obstructed path, amplitudes significantly above the system noise level were received. A periodicity in the signal amplitude, of about 12 to 14 cycles per 20 meter interval, occurs somewhat uniformly on both sides of the transmitter midpath. This result is believed to be due to a grating effect caused by the grid-like pattern of location of the individual trees in the orchard. The data from Figure 4.25 and data from a second run are shown in Figure 4.26. A mistake in antenna tracking caused the 28.8 and 57.6 GHz data record shown in the light trace of Figure 4.26 to be in error for the region between -100 to -20 meters. The receiver antenna pointing was corrected at about the -20 to -15 meter point on the arc. The two records shown in Figure 4.26 display the repeatability of signal amplitude relative to large scale terminal position change, after correct pointing was established. Variability in the travel of the transmitter and/or in the tracking by the receiver cause the off-set of the respective traces, especially on the 28.8 and 57.6 GHz data where the receiving antennas have beamwidths of $\pm$ 0.6°. There are features with symmetry about the center of the arc in terms of peak amplitudes at about $\pm$ 25 meters and $\pm$ 50 to 60 meters due to tree alignment. The outer edge of the orchard was not symmetrical; there were more trees in the path to the left of center (negative distance) than to the right of center. This is the reason the signal losses were greater on the left side of the record in Figure 4.25 and also the reason for a slight non-symmetry in position of peak levels around the $\pm$ 50 to 60 meter distances.

At the center of the arc, between tree rows, the required spacing for first Fresnel radius at midpath (r_{max}) is calculated by

$$r_{max} = \frac{1}{2} (d\lambda)^{1/2}$$

where d is the path length and λ is the rf wavelength. For the 720 m path (Figure 4.25) at 9.6, 28.8, and 57.6 GHz, r_{max} is 2.4, 1.37, and 0.97 meters, respectively. A first Fresnel radius clearance was exceeded in all directions except over ground on this path. For the shallow angle between the direct path line and the line to the surface at midpath, the ground probably acted as a reflecting surface more than a diffracting surface. However, there is not enough information on the effective reflection coefficient and phase of the reflected signals available to estimate its effect on the received signal. A ground reflection of this type may account for some of the approximately 2 to 3 dB reduction in signal from the free space value,

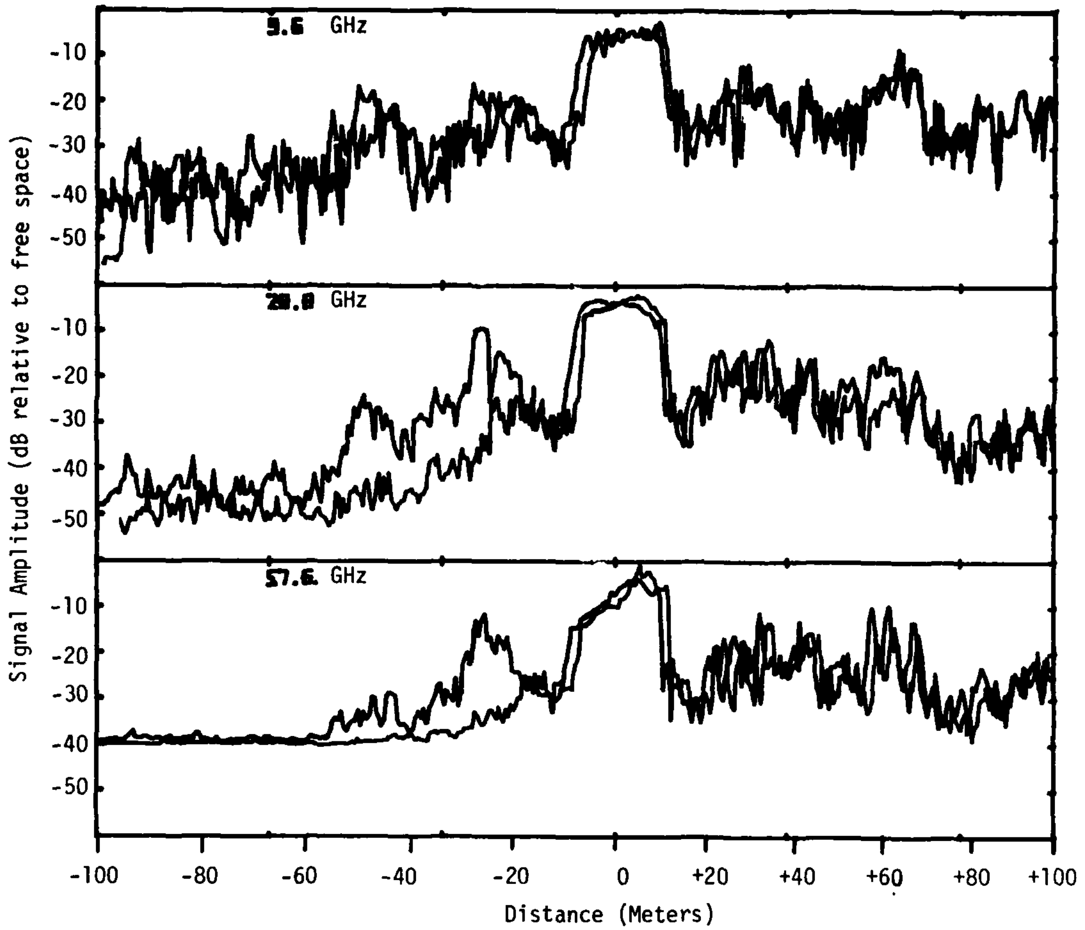

Fig. 4.26. Received signal amplitude for two runs as a function of scan distance on a 720 meter propagation path (April 1982).

but the fact that all frequencies show about the same reduction seems unusual. The measurement accuracy at the upper two frequencies is probably not better than -2 dB because of the manual antenna tracking used for this measurement. A strong multipath component from a tree trunk near midpath would have the appropriate delay path geometry to cause the slope of the 57.6 GHz signal amplitude near the center of the arc (Figure 4.25 and 4.26). A ground reflection seems to be ruled out because the rate of signal change is too great for the path delay difference relative to wavelength for the ground clearance and path length involved. Poor antenna tracking is not a likely source because the 28.8 and 57.6 GHz channels would be affected similarly.

A second set of measurements was made with the receiver at R_{13} and the transmitter at TM_2. This path is 620 meters long and the arc over which the transmitter moved from A to B was 80 meters. This path was line-of-sight (LOS) for only a very small segment at midpath and at that point, the transmitter and vehicle were visible with the aid of binoculars. The receiving antennas did not track the movement of the transmitter for this test and some evidence of signal roll-off due to non-alignment of the antennas is apparent in the data in Figure 4.27. The data in Figure 4.28 shows a retrace of the data in Figure 4.27 and data from a second run. At 9.6 GHz, the receiving antenna beam 3 dB points are at $\pm$ 27 meters of the arc on the distance scale of Figures 4.27 and 4.28. The 28.8 and 57.6 GHz receiving antennas had 3 dB beamwidths of $\pm$ 6.5 meters on the arc and by $\pm$ 30 meters each signal would be at least 30 dB below the main beam level. Taking these beamwidths into account, the received signal amplitude characteristics for the 80 meter scan at 9.6 GHz is quite similar to the values recorded at 28.8 GHz. At 57.6 GHz, the obvious difference is the rapid signal drop-off at either side of the narrow LOS aperture. The reason for this is not clear to the authors and it did not appear on azimuth and elevation angle scans taken at this LOS aperture. For the wide aperture path (Figure 4.26) with greater than first Fresnel zone clearnace, the signal drop-off was sharp for each frequency which may suggest that the 57.6 GHz signal showed the sharp drop-off because it was nearest to having first Fresnal zone clearance. Otherwise, the explanation could lie in a happenstance of position of reflecting surfaces and the frequency dependence of signal phase on multipath interference.

For the narrow aperture path, the diameters of the cross section varied from 0.2 to 0.6 meters. This results in less than half the midpath r_{max} for first Fresnel zone clearance at even the highest frequency. As seen in Figure 4.27 the signal amplitude was 10 to 12 dB below the free space value when optimum (maximum signal amplitude) antenna pointing was used at the LOS portion of the path.

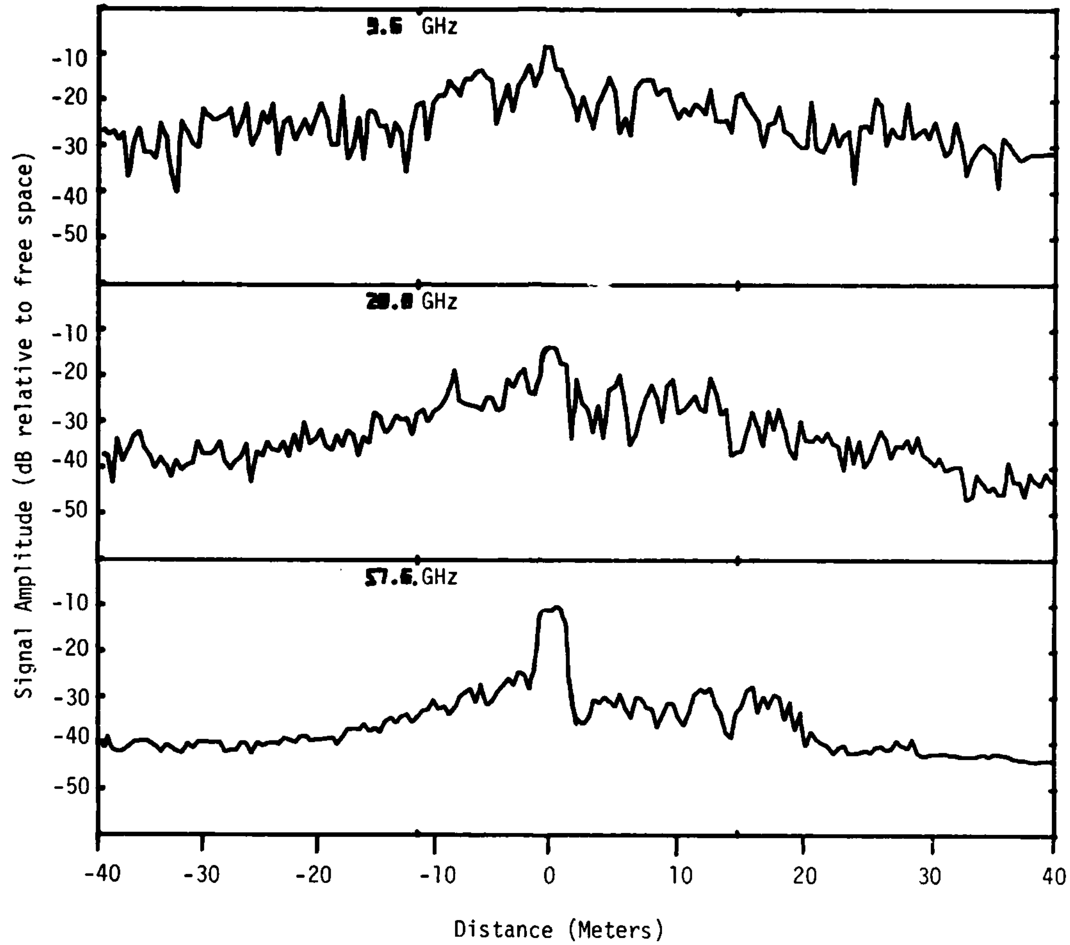

Fig. 4.27. Received signal amplitude as a function of scan distance on a 620 meter propagation path (April 1982).

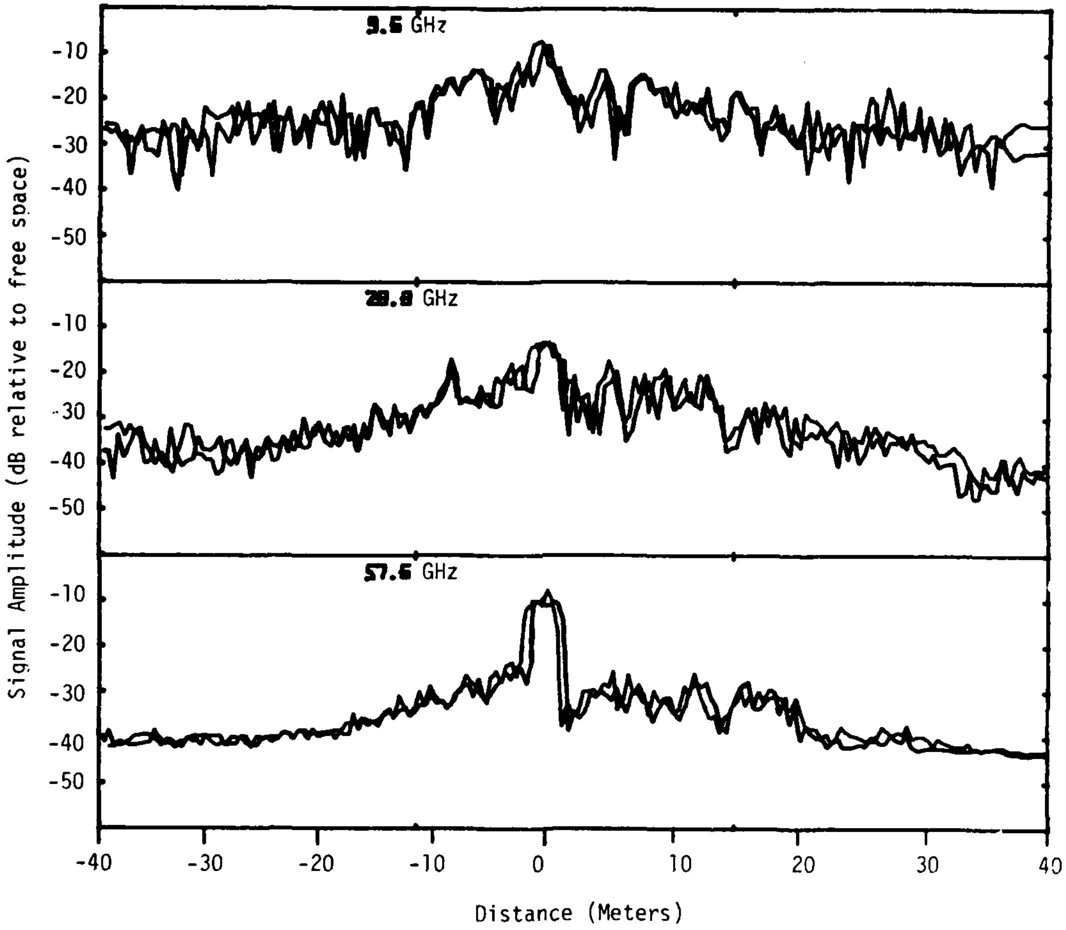

Fig. 4.28. Received signal amplitude for two runs as a function of scan distance on a 620 meter propagation path (April 1982).

With the trees in leaf in August, a test similar to the TM_1 - R_{13} test was run using TM_1 and R_{17}. The scan was limited to ± 50 meters and the path length was 507 meters. Although the receiver and transmitter (at midpath) were located between rows as in April, the path for the measurement was obstructed by leaves from the branches extending into the space between rows because of the added weight from the leaves. The data in Figure 4.29 are from two runs with the transmitter moving from left to right on TM_1 in Figure 3.3. The results obtained from these runs are similar to the earlier results (without leaves) shown in Figures 4.25 and 4.26 except the peak levels near midpath are reduced in amplitude. The periodic amplitude ripple is still present at about 13 to 15 cycles for a 20 meter interval due to trunk or tree spacing. Also a hint of symmetry exists approximately at ± 20 and ± 40 meters.

E. Horizontal Displacement Scans

A distant view of the orchard gives an impression of very uniform and symmetrical pattern of trees. However, a tree-to-tree inspection shows obvious differences in branch sizes and heights, as well as nonsymmetry in branch distribution. Some variability in measured losses is apparent in Figures 4.1 through 4.12 and much of this is presumed due to this nonuniformity which contributes to differences in absorption losses, in addition to changes in reflection, diffraction, and scattering components. These variations in measured values are a function of position, horizontal offset, vertical offset, and azimuthal and elevation pointing. To study the range of this variability, position scan measurements were made with the transmitter fastened to a track which allows movement in the horizontal plane.

Several tests were conducted by moving the transmitter from 0.7 meter to the left of center to 0.7 meter to the right of center and recording the received signal amplitude during this transition. The data in Figures 4.30, 4.31, and 4.32 show the results of these measurements at operating heights of 1, 4, and 6 meters, respectively, for three trees without leaves in the path. Two traces are shown for each frequency. The traces with least variations were recorded with the transmitter located in the open field at TX_3, about 300 meters from the nearest tree, and the receiver at R_4. With this configuration, little variation in received amplitude was observed as a horizontal scan was performed. The traces with large variations represent the received signals with the transmitter located in the orchard at location R_4 and with the receiver in the clearing at location TX_3. This arrangement places the transmitter in proximity with the trees and causes considerable variation in received signal amplitude as a function of horizontal position. Level changes

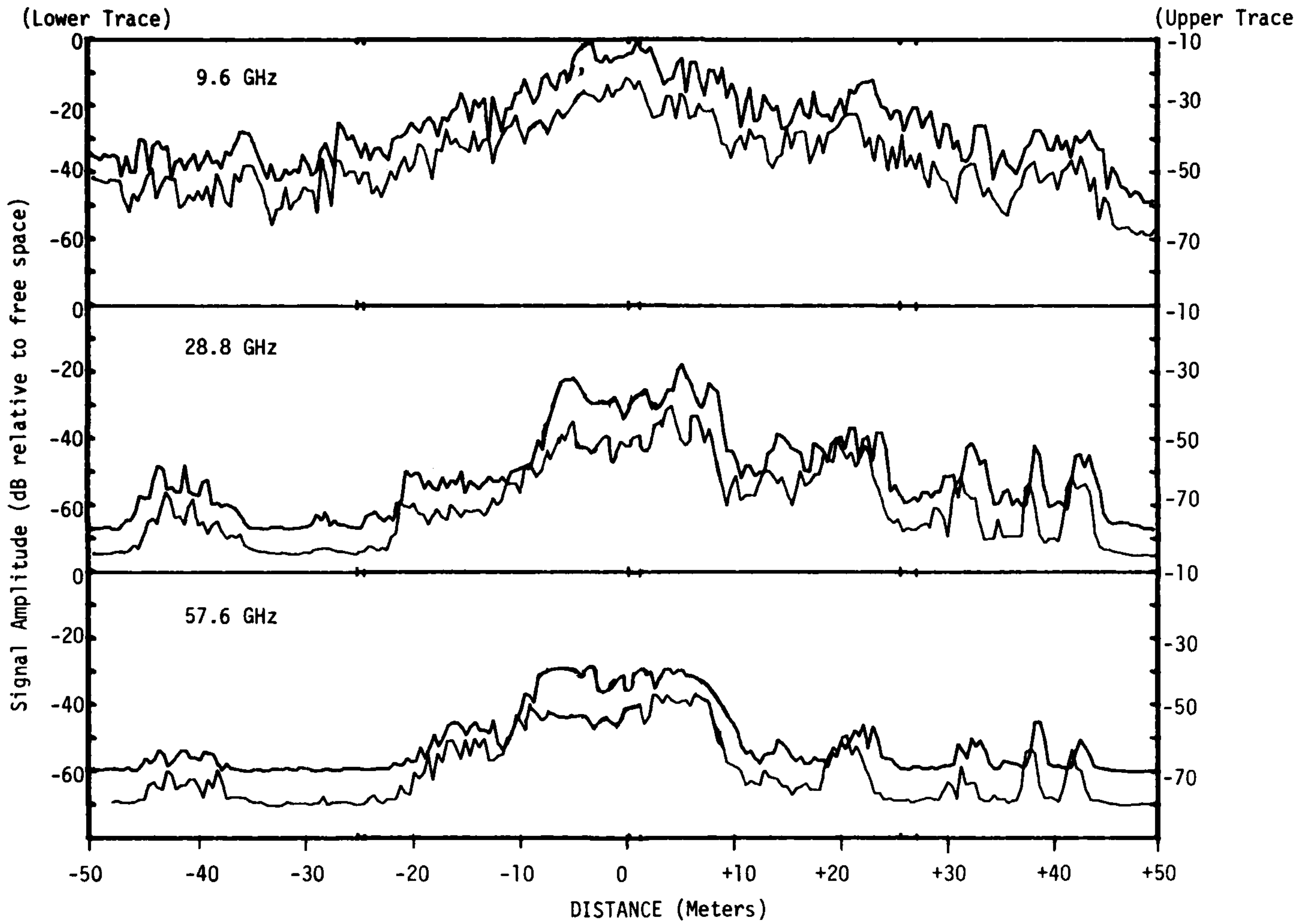

Fig. 4.29. Received signal amplitude for two runs as a function of scan distance on a 507 meter propagation path. The trees were in full leaf (August 1982).

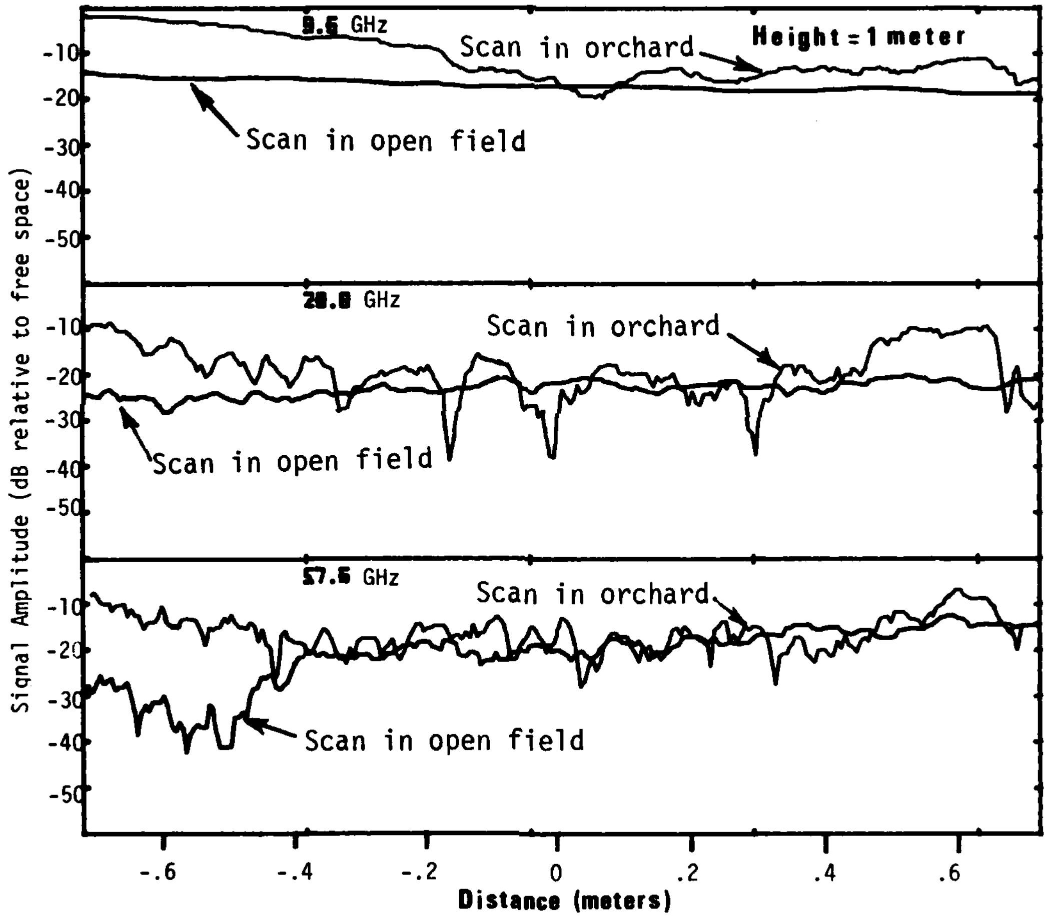

Fig. 4.30. Received signal amplitude as a function of transmitter horizontal position with the transmitter in the orchard and with the transmitter in an open field. Measurements at 1 meter with 3 trees and no leaves.

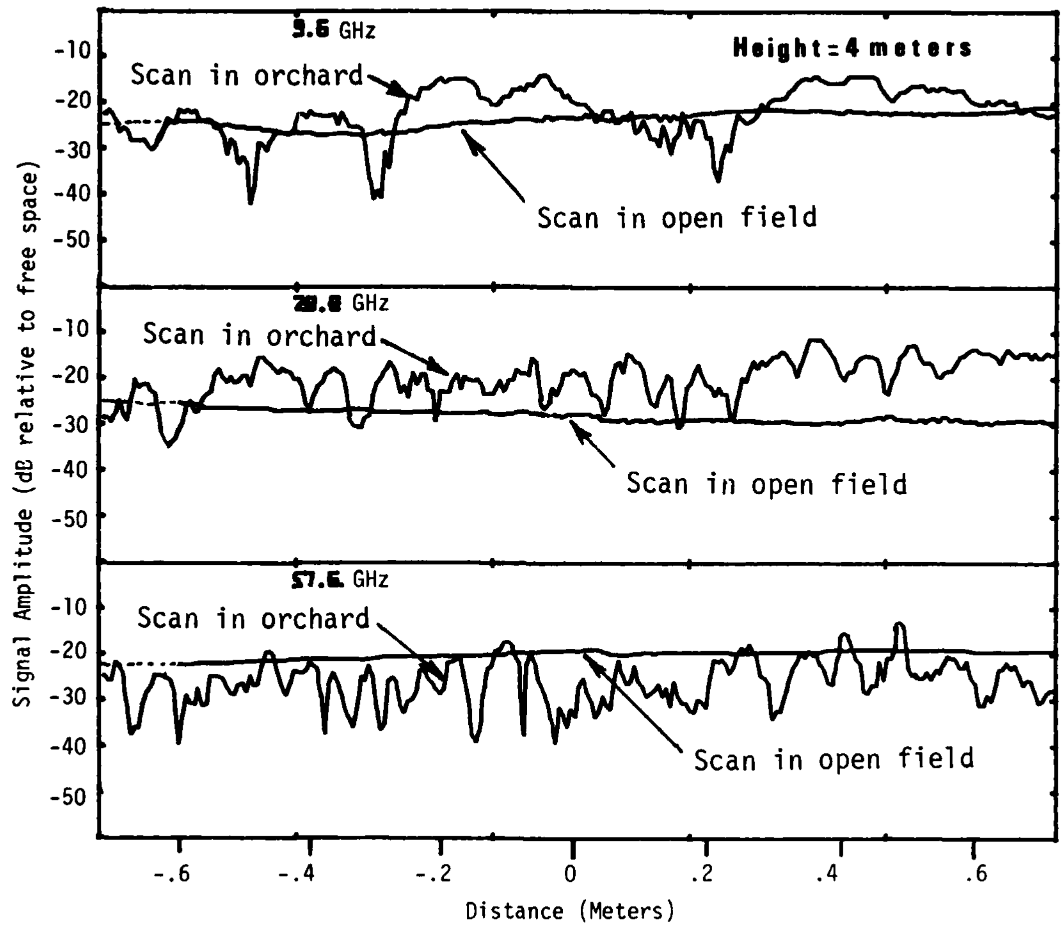

Fig. 4.31. Received signal amplitude as a function of transmitter horizontal position with the transmitter in the orchard and with the transmitter in an open field. Measurements at 4 meter with 3 trees and no leaves.

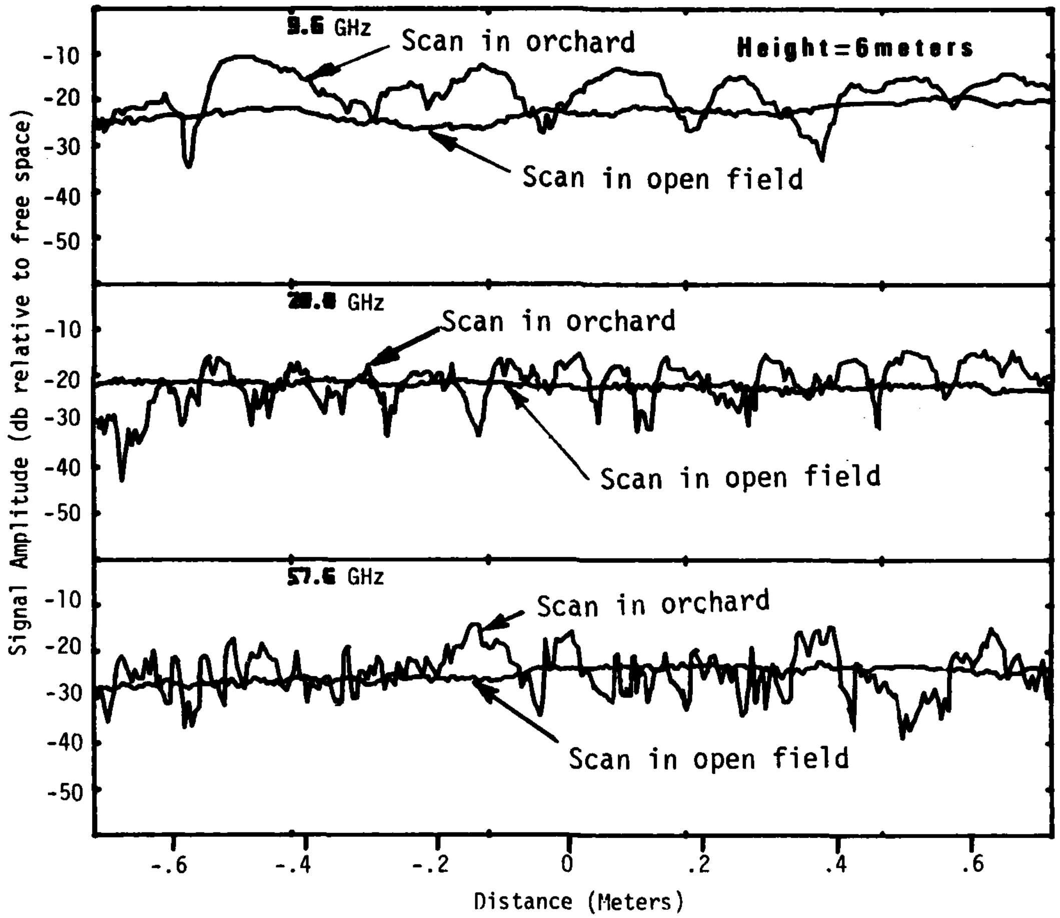

Fig. 4.32. Received signal amplitude as a function of transmitter horizontal position with the transmitter in the orchard and with the transmitter in an open field. Measurements at 6 meter with 3 trees and no leaves.

greater than 20 dB are observed in these data. The rate of change of signal level appears to be proportional to frequency suggesting multipath signals with constructive and destructive phase interference at the receiver antenna apertures. This characteristic of relative deep fading seems surprising because for each position of the transmitter there are numerous branches blocking the LOS path especially at the 4 and 6 meter heights. To obtain deep fades of this type, two strong signal paths of slightly different propagation delays are required. If many paths with random signal phase existed, deep fades would not be seen. At the 1 meter height, Figure 4.30, the transmitter antennas are close to grazing the side of the row of trunks at the positions $\pm$ 0.7 meters from the center location only a few meters behind the first of the three trees in the path. A portion of the transmitter antenna may even be LOS at the extremes of horizontal travel, but in any case, the received signal level increases at these extremes from a minimum at the center of scan. For the 1 meter path height, there is little likelihood of multipath from tree trunks of adjacent rows because these are not illuminated by either the $\pm$ 5 degree transmitting antenna or the $\pm$ 0.6 receiving antenna (28.8 and 57.6 GHz) beams. Near midpath, ground reflections would produce only a fraction of a wavelength of path change for the $\pm$ 0.7 meter horizontal position change, even if the direct path were not obstructed by tree trunks. This fact was verified on a 300 meter unobstructed path in calibrations for depolarization measurements.

The above observations are presented in order to support an argument that signal variations seen in the position scans are not primarily a result of multipath interference, but are variations in diffracted signal levels from trunk and branch surfaces, where numerous diffractors and path geometry changes occur as a function of position. Because the position scans, with the transmitter some distance away from the trees, produced little change in signal level it is logical to assume the trunks and branches nearest the antennas being scanned have the largest influence on the observed signal variations. This seems reasonable, as well, since the highest field intensity occurs at the obstructions nearest the transmitter. The reason that the number of signal variations with position change appears to be proportional to frequency is believed to be a result of surface or edge roughness which will exhibit the same sort of frequency dependence as multipath fading. Although it is difficult to describe the paths taken by these signals during a a position scan, it is believed that it is not by means of discrete multipath reflections. Regardless of the mechanism, this data allows a view of position dependence and provides an indication of the potential range of excursions for the measured vegetation loss data presented earlier in this report.

A second set of data was recorded in August, with leaves on the trees. Essentially the same locations were used as for the measurements discussed above with the transmitter in the orchard. The receiver was at TX_{3A} and the transmitter was at R_4. The path length was 350 meters and 3 trees were on path. These data are plotted in Figures 4.33, 4.34, and 4.35 for heights of 1, 4, and 6 meters, respectively, displaying signal amplitude variations for horizontal scans in trees with leaves and with no leaves. At 1 meter, Figure 4.33, the signal levels are similar except with leaves, the trace shows a slightly lower level to the left of center and a higher level to the right of center. Because the soil under the trees had been plowed and disked between April and August, some terminal markers were lost which produced about a $\pm$ 0.5 meter uncertainty in distance from base of tree and about a $\pm$ 0.25 meter uncertainty in location of the center line of path. This uncertainty and the possibility that branches drooped lower due to weight of leaves probably accounts for this difference. At the 4 and 6 meter heights, outside of the added path loss, the horizontal scan with leaves showed somewhat less peak to peak variation but the number of signal variations for the entire scan was almost the same for all three frequencies. This is probably due to the absorption of signal by the leaves and the considerable increase in the number of edge diffractors.

F. Vertical Scans (Receiver Only)

In the process of recording data for the vegetation loss measurements discussed in section IV A, the transmitter and receiver terminals were positioned first at the 1 meter height and then at the 4 meter and 6 meter heights. Recordings were made while the receiving terminal was moved from the 1 meter height to the 4 meter height, for three settings with three trees on path and for three settings with eight trees on path. During this transition the transmitter terminal was stationary at the 1 meter height. These results are shown in Figures 4.36 and 4.37 for a path length of 350 meters (3 trees) and a path length of 420 meters (8 trees), respectively. During these transitions the signal amplitudes are reduced in accordance with the increased foliage depth at the 4 meter height compared to the foliage at the 1 meter height. The differential between traces at any given height is due to small differences in receiver antenna pointing and in the location of the receiver (vehicle) for each of the six runs, with also the possibility of slight differences in tree mass produced by wind motion. These data show the signal variations as a function of height and the average signal rolloff with increased height.

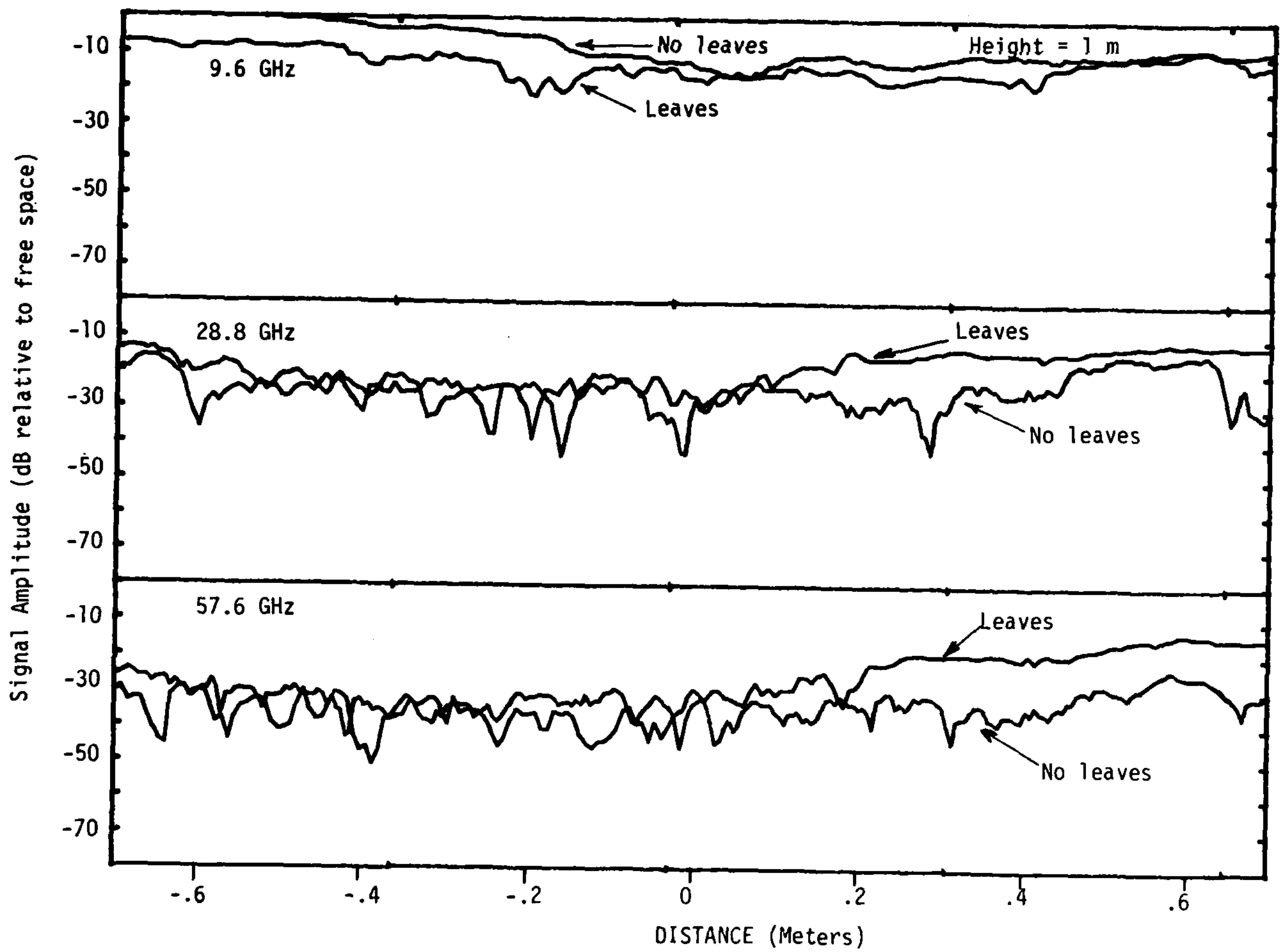

Fig. 4.33. Received signal amplitude as a function of horizontal position with the transmitter in the orchard (with leaves and without leaves). Measurements at 1 meter with trees in path.

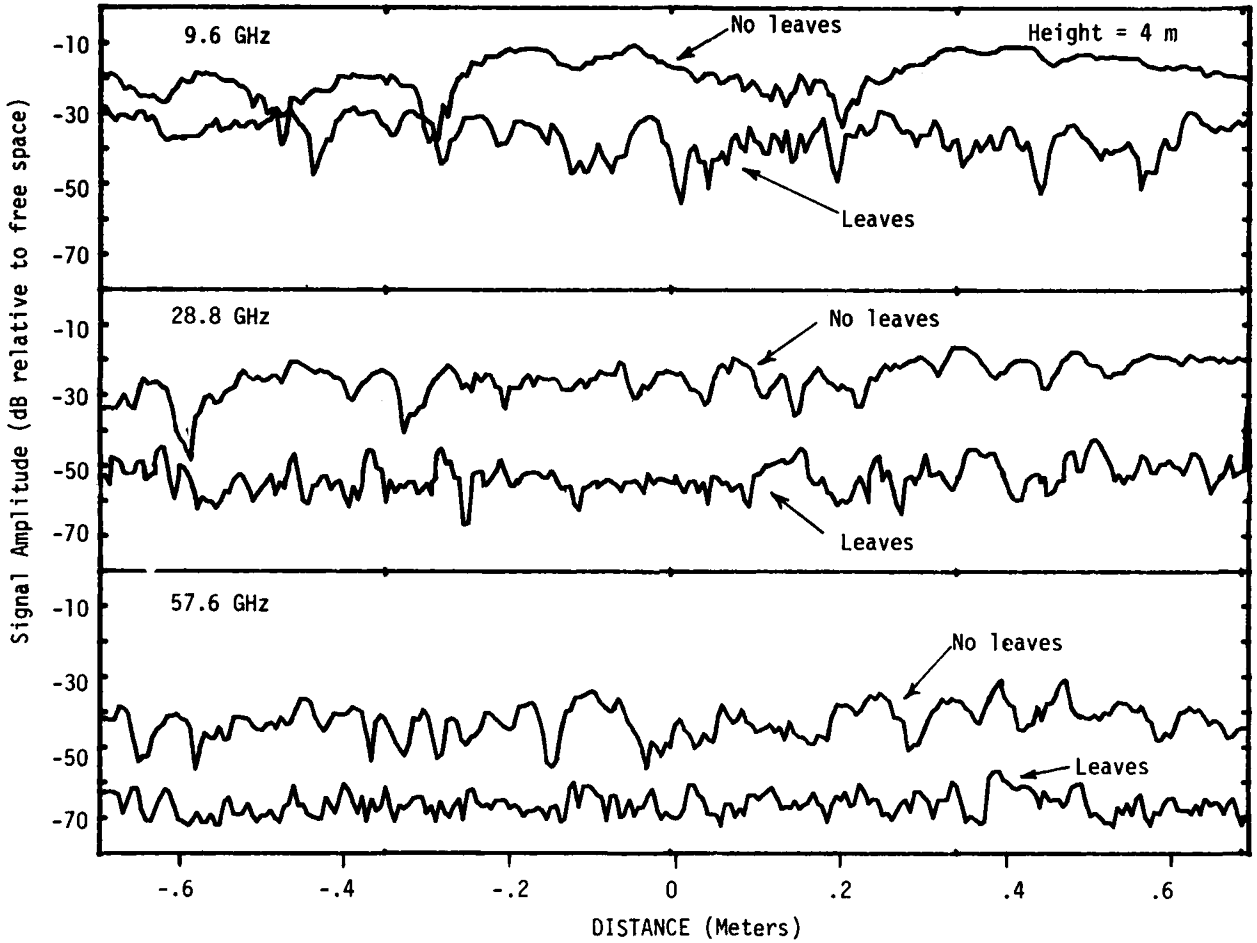

Fig. 4.34. Received signal amplitude as a function of horizontal position with the transmitter in the orchard (with leaves and without leaves). Measurements at 4 meters with trees in path.

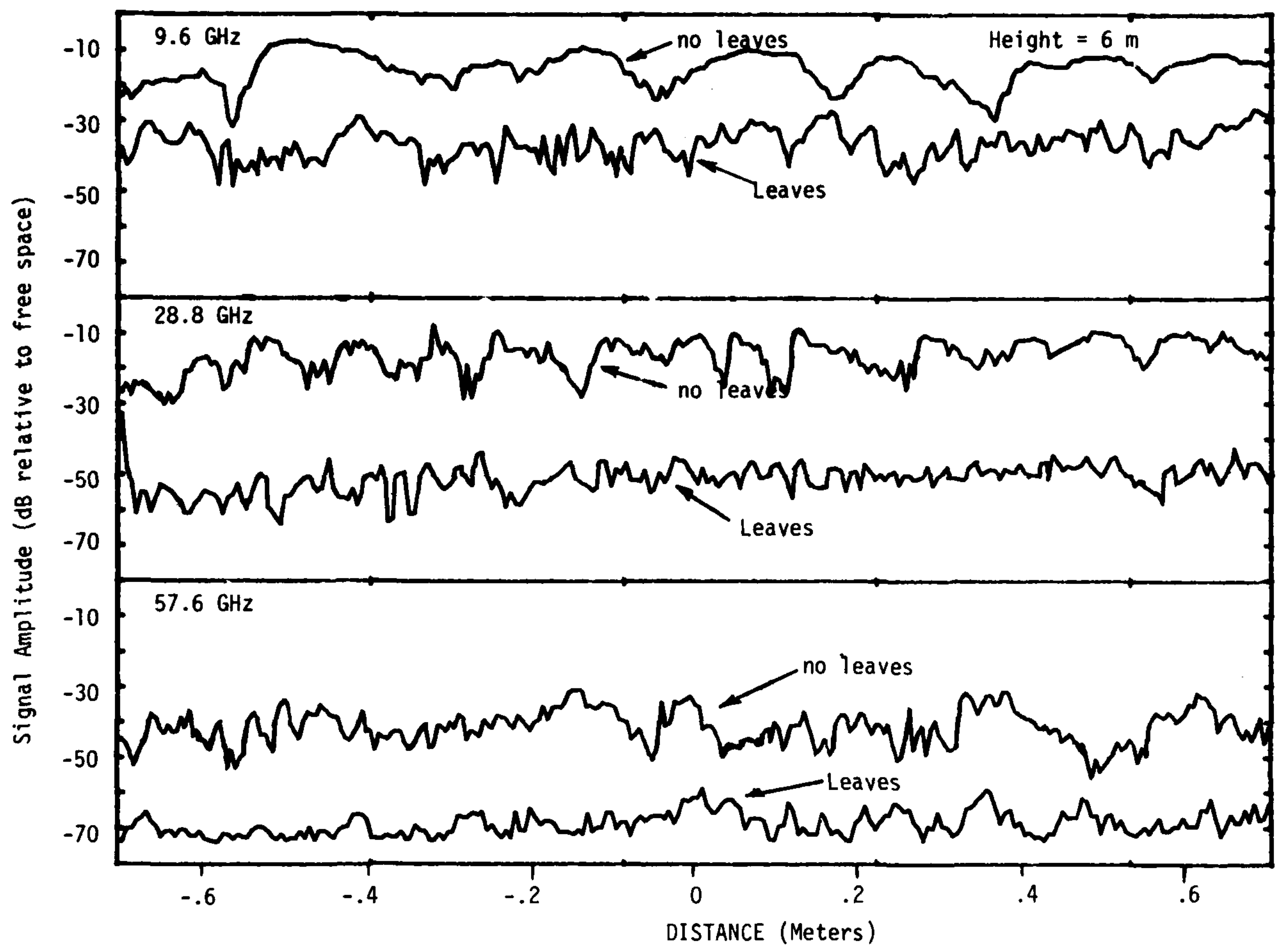

Fig. 4.35. Received signal amplitude as a function of horizontal position with the transmitter in the orchard (with leaves and without leaves). Measurements at 6 meters with trees in path.

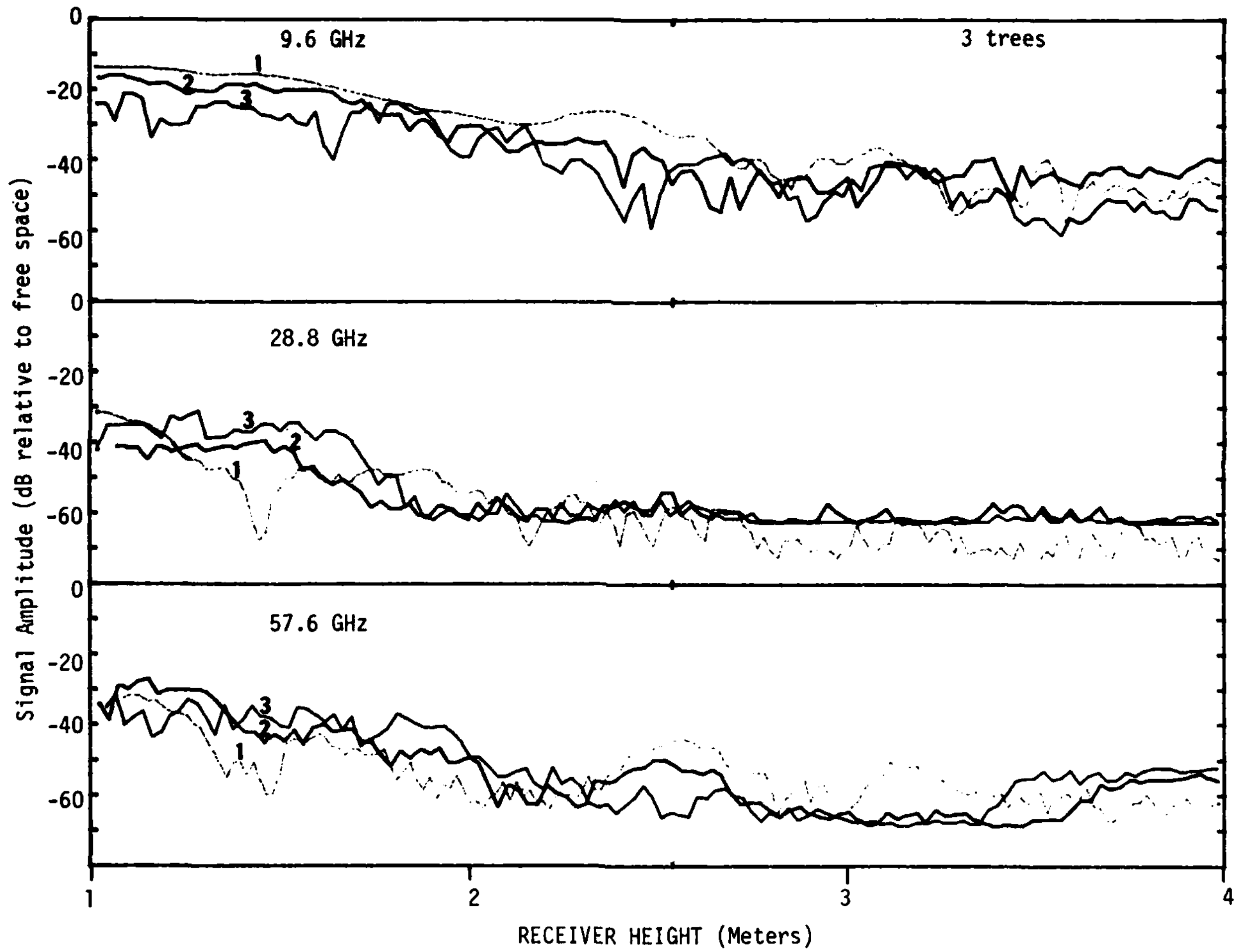

Fig. 4.36. Received signal amplitude as a function of receiver height with the receiver in the orchard. Measurements with 3 trees in leaf on path.

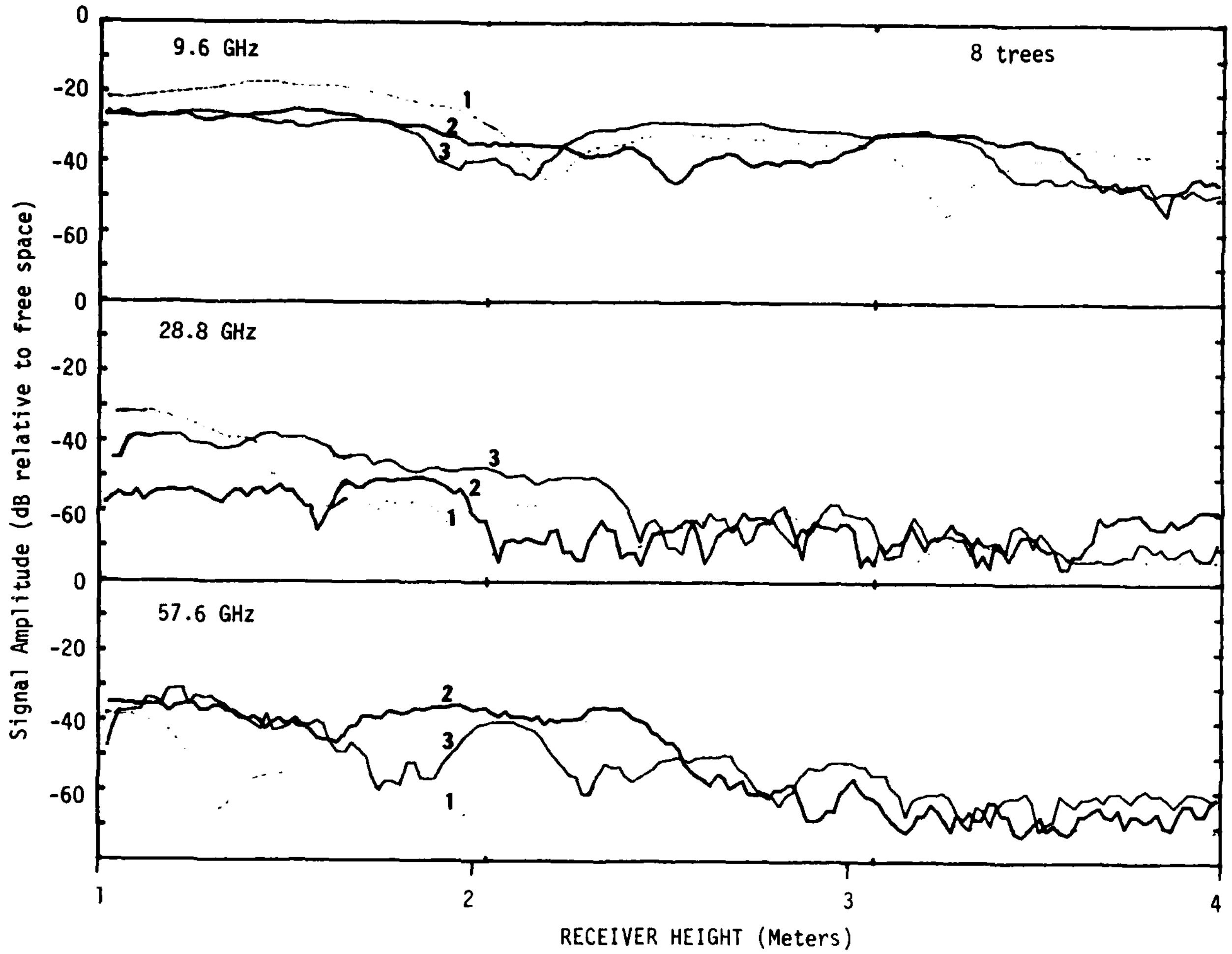

Fig. 4.37. Received signal amplitude as a function of receiver height with the receiver in the orchard. Measurements with 8 trees in leaf on path.

G. Cross-polarization (Horizontal Scans)

A comparative set of horizontal scan measurements were made on a 420 meter (8 tree) path with leaves, first with both the transmitting and receiving antennas vertically polarized and then with the transmitting antennas horizontally polarized and with the receiving antenna vertically polarized. The second set shows the effect of horizontal scanning with the antennas cross-polarized. These data were measured in a manner similar to the data discussed in section IV D. The resulting measurements for heights of 1, 4, and 6 meters are shown in Figures 4.38, 4.39, and 4.40, respectively. In all these data, the signal amplitude variations as a function of horizontal position are of comparable magnitude, except for the 57.6 GHz data at 6 meters (Figure 4.40). In these traces the vertical-vertical data and the horizontal-vertical data are barely above the noise level of the system. Signal depolarization is evident in the data, but these are difficult to assess due to the range of signal amplitude deviation with antenna horizontal position. As would be expected, the greatest amount of depolarization occurred for the densest foliage or at maximum signal loss. For the portion of the scans, at all three frequencies over which the VV and VH signal levels were equal, it can be assumed that the received signal was totally depolarized. This degree of depolarization also suggests that scattering modes of propagation account for a considerable amount of the signal reaching the receiver for the 8-tree path examined.

H. Receiver Position Relative to the First Tree on Path

In an attempt to determine the effect on vegetation loss, due to the proximity of the receiving antennas to the closest tree in a row (with the receiver in the orchard), a duplicate set of measurements was made: first with the receiver 25 meters from the nearest tree and then with the receiver 7 meters from the nearest tree. Two independent measurements were made with three defoliated trees on path for each set, one on a nominal path of 122 meters and the second on a nominal path of 338 meters. The results of these tests are shown in Figure 4.41. The open symbol data are with the receiver at 25 meters distance from the closest tree and the closed symbols represent readings with the receiver 7 meters back from the nearest tree. The data are shown for the 1, 4, and 6 meter heights and the two path lengths. The trend in these data is that less vegetation loss is observed with the receiver set back 25 meters compared to a set-back of 7 meters. These results might be explained by the fact that the additional clearance between the last tree on path and the receiver places more diffracted or scattered components

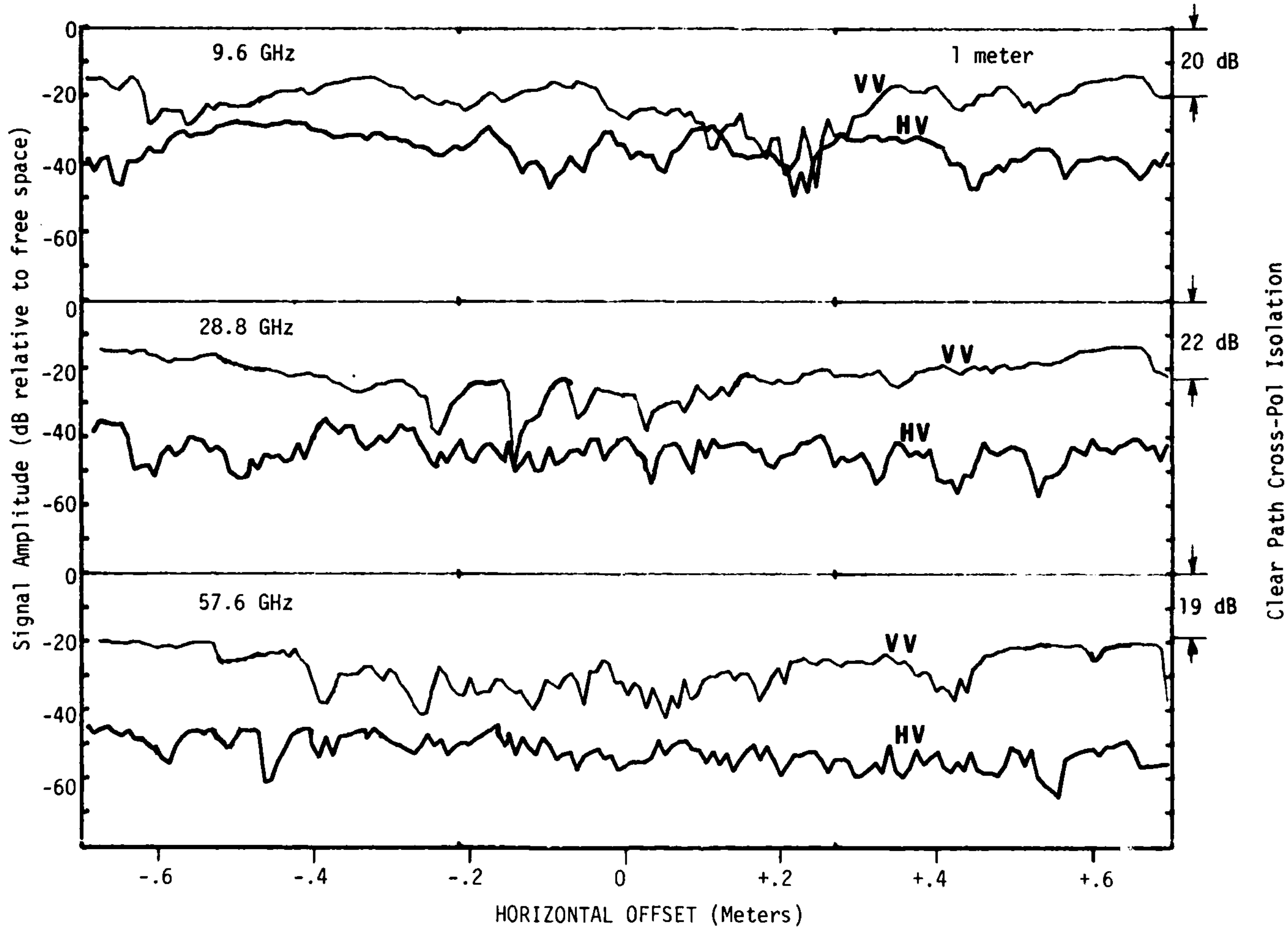

Fig. 4.38. Received signal amplitude as a function of horizontal scan comparing signals with antennas linearily and cross-polarized. Measurements with 3 trees in full leaf on path. Terminals at 1 meter.

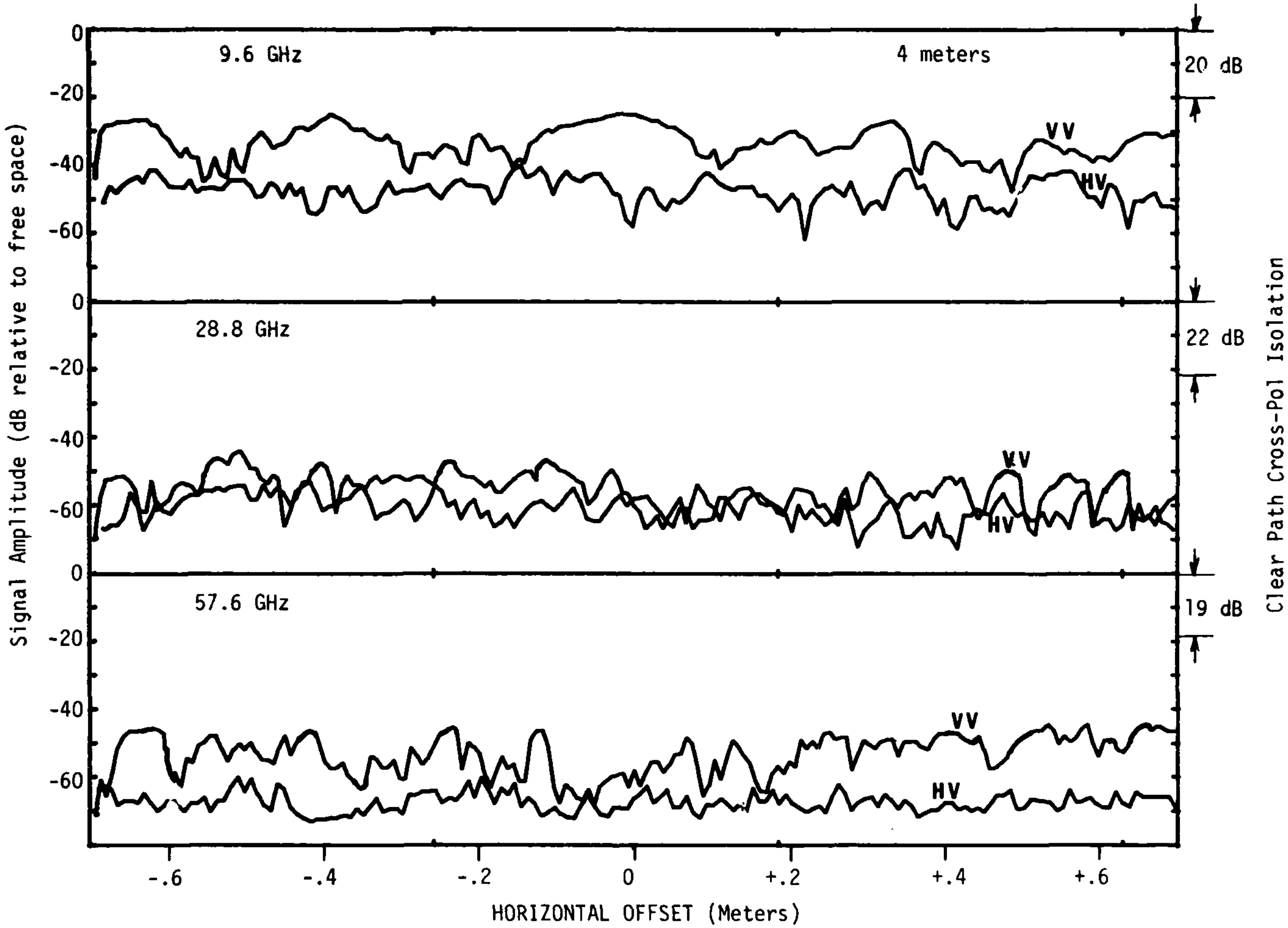

Fig. 4.39. Received signal amplitude as a function of horizontal scan comparing signals with antennas linearily and cross-polarized. Measurements with 8 trees in full leaf on path. Terminals at 4 meters.

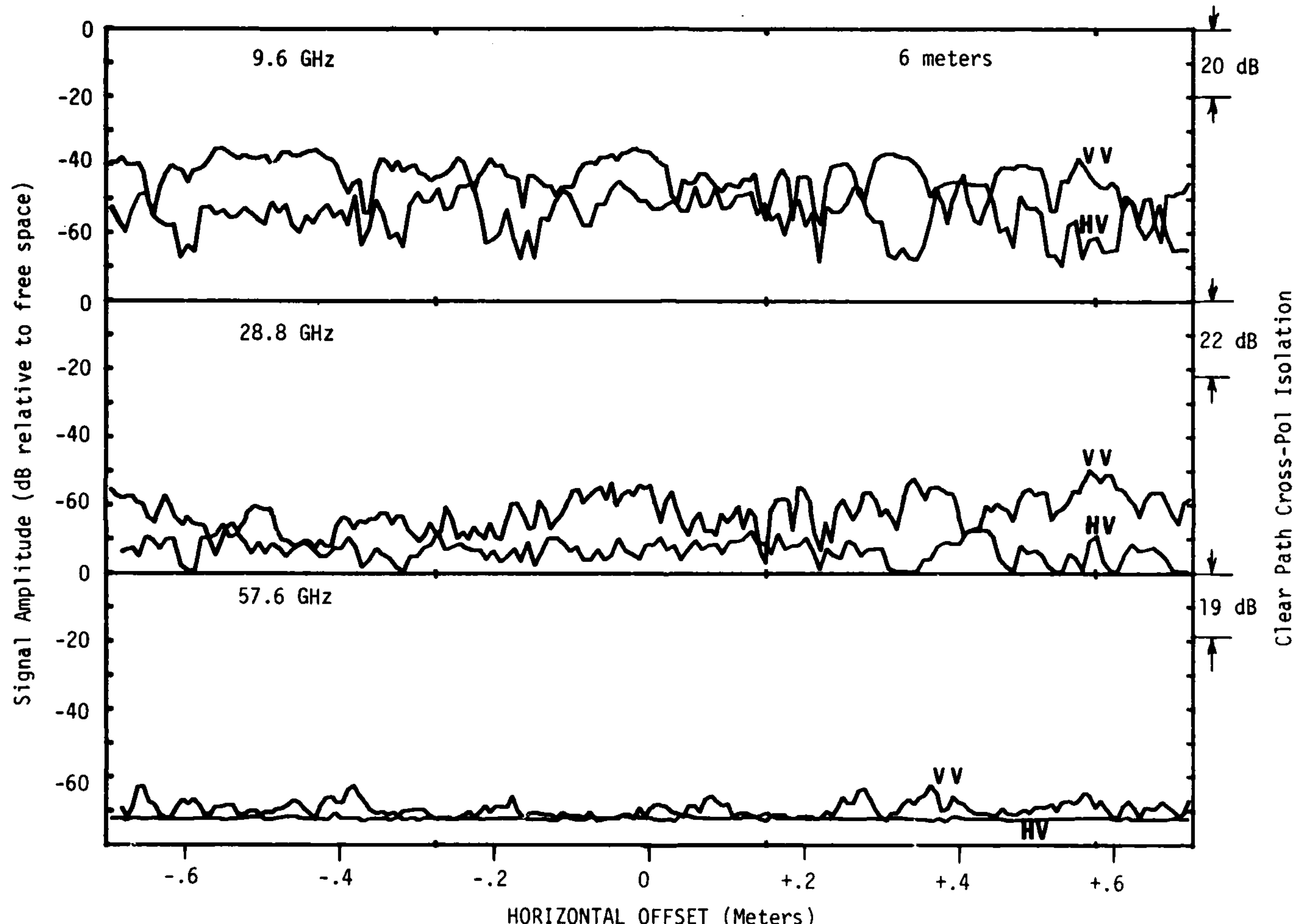

Fig. 4.40. Received signal amplitude as a function of horizontal scan comparing signals with antennas linearily and cross-polarized. Measurements with 8 trees in full leaf on path. Terminals at 6 meters.

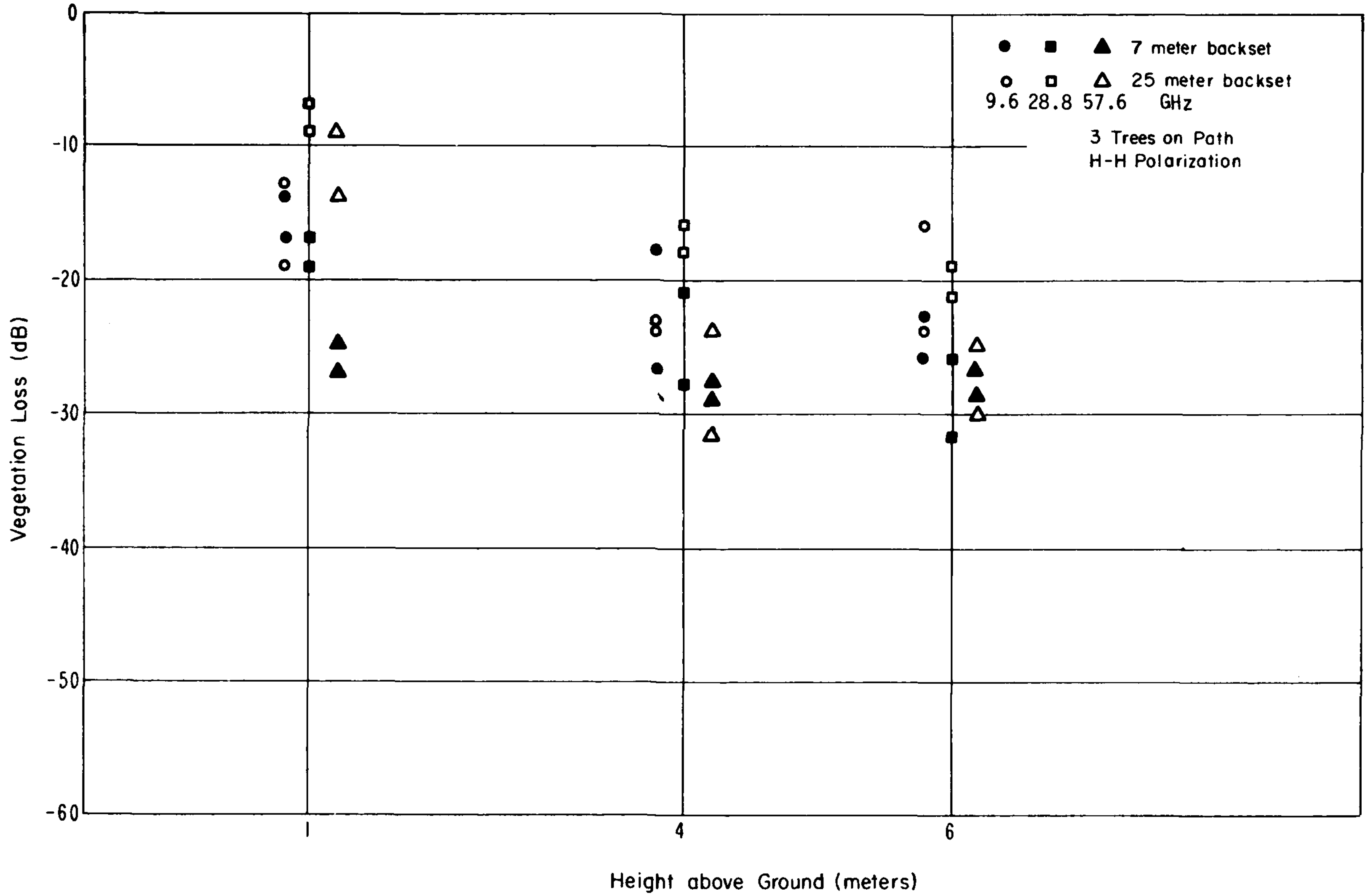

Fig. 4.41. A comparison of received signal amplitude as a function of receiver terminal proximity to nearest tree on path. Values with open symbols were measured at 25 meters distance from terminal to tree and closed symbols for 7 meter separation.

within the beam of the antenna. The spacing between trees in the row prevented additional measurements at greater set-back distances. Similar measurements made with leaves on the trees, did not indicate this trend. With the trees in full leaf, the space between rows was nearly filled with leaves and the set-back differential that could be attained was reduced
to 6 meters.

V. CONCLUSIONS

Measurements at 9.6, 28.8 and 57.6 GHz were made to describe vegetation loss. A well-established, uniformly planted pecan orchard was chosen because the density of foliage was very constant with distance. At tree trunk height (1 meter with no underbrush) and at branch heights with trees in a defoliated state (early spring), the vegetation loss curve takes on a decreasing, nearly linear shape as a function of number of trees. In contrast, at branch height (4 and 6 meters) in a foliated state, the curve makes an abrupt break at a foliage depth of about 30 meters. For the first 30 meters of foliage depth, the increase in vegetation loss is nearly linear at a rate of 1.3 to 2.0 dB per meter, depending on frequency, and beyond 30 meters the curve decreases at an exponential rate that averages only 0.05 dB loss per meter. The shape of the vegetation loss curve as a function of foliage depth is interpreted as an initial loss rate due to the high attenuation of the direct path mode, and beyond 30 meters, a low-loss rate due to the multiple scatter mode. These data also show a clear trend for increased losses with increased frequency but not in a directly proportional relationship, i.e., higher frequencies were attenuated less than the ratio of the increase in frequency. These ratios of vegetation losses versus frequency appear to be related to the wavelength of the propagated wave compared to the scale size of the leaves and branches obstructing the path. This relationship cannot be determined from measurements at the three frequencies used, but there may be little increase in loss above a foliage dependent frequency as suggested by the data. This is expected based on the frequency dependence of Mie calculated scattering losses for rain[3].

Measurements taken with one terminal traversing just outside the orchard indicated that, with state-of-the-art receivers, receptions can occur at far greater foliage depths than would have been anticipated. These data also showed a considerable variation in received signal level with small terminal position changes (fraction of meters) in either a horizontal or a vertical direction. As foliage depth increases, the propagated wave looses greater portions of its directional and polarization identity. Because of these changes in properties, which also include time delay distortion, the usable coherent signal bandwidth will be limited.

It is hoped that future measurements can be conducted to compare the deciduous results to a conifer type of foliage. A study of the frequency dependence of individual elements of vegetation, leaves, needles, branches, etc., in terms of dielectric, absorption, and diffraction properties by performing controlled experiments in an anechoic chamber is also proposed. Channels that are obstructed will be examined by the nanosecond-resolution impulse probe which is a part of the mm-wave diagnostic probe[4] to evaluate channel distortions as a function of foliage depth.

VI. REFERENCES

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